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(54) **TIME AND FREQUENCY SYNCHRONIZATION IN MULTI-INPUT, MULTI-OUTPUT (MIMO) SYSTEMS**

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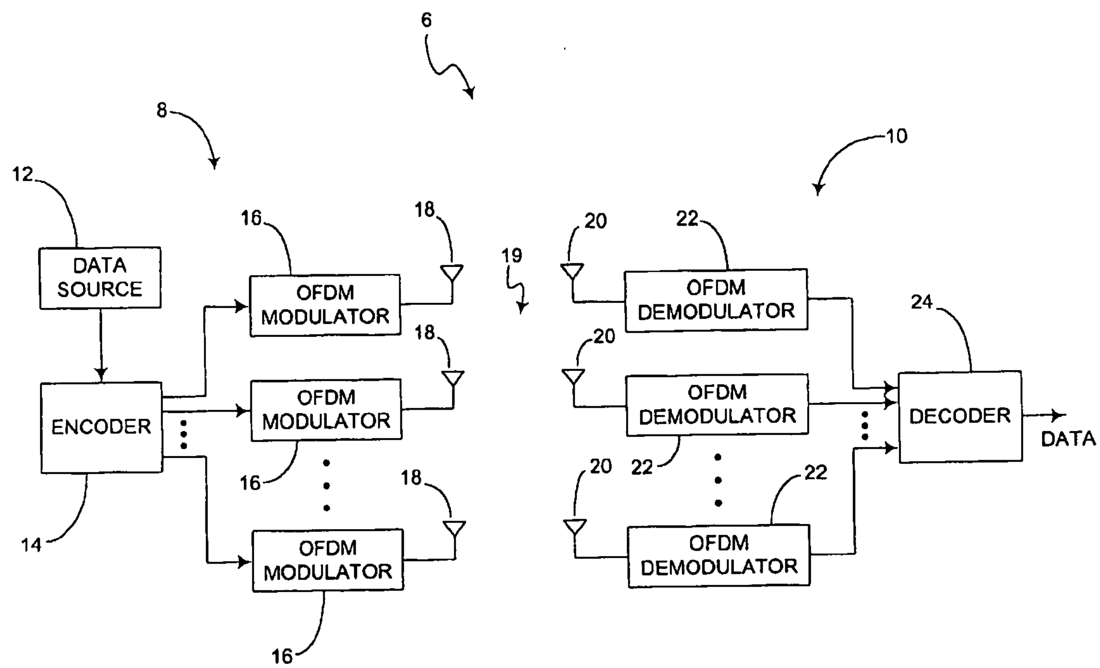
(57) **ABSTRACT**

In a communication system, and in particular a wireless Orthogonal Frequency Division Multiplexing (OFDM) communication system, the present invention provides systems for synchronizing data transmitted across a channel. The present invention may be used in a Multi-Input, Multi-Output (MIMO) system in which the data is transmitted from any number of transmitting antennas and received by any number of receiving antennas. The number of transmitting and receiving antennas does not necessarily have to be the same. Circuitry is provided for synchronizing the data in both the time domain and frequency domain. Time synchronization involves coarse time synchronization and fine time synchronization. Frequency synchronization involves coarse frequency offset estimation, fine frequency offset estimation, and frequency offset correction.



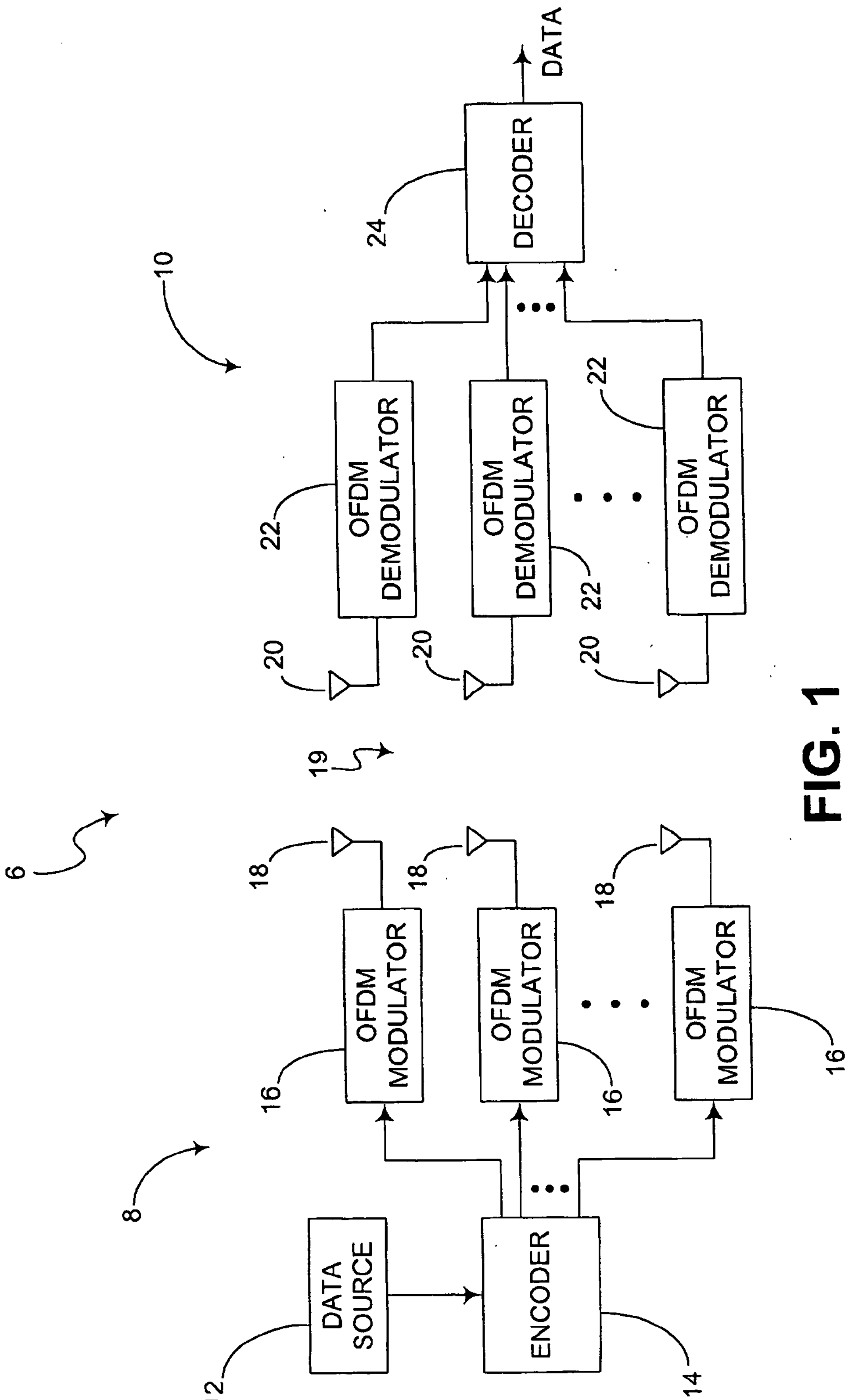

DATA SOURCE
12
ENCODER
14
8
OFDM MODULATOR
16
18
6
19
OFDM DEMODULATOR
20
22
10
DECODER
24
DATA

FIG. 1

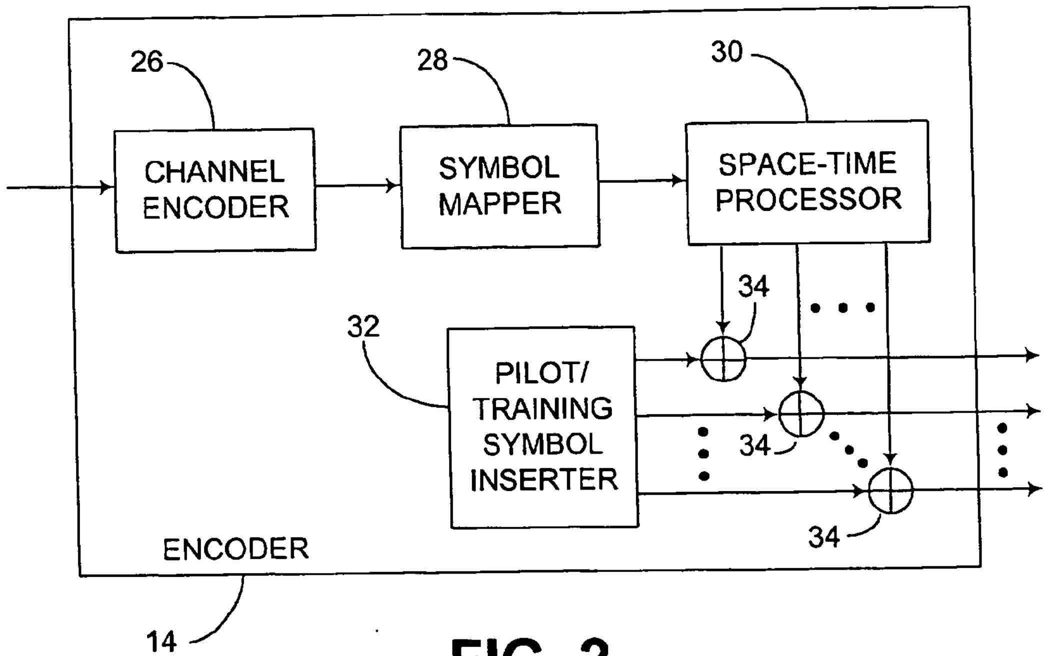

26
28
30
CHANNEL ENCODER
SYMBOL MAPPER
SPACE-TIME PROCESSOR
34
32
PILOT/ TRAINING SYMBOL INSERTER
34
34
ENCODER
14

FIG. 2

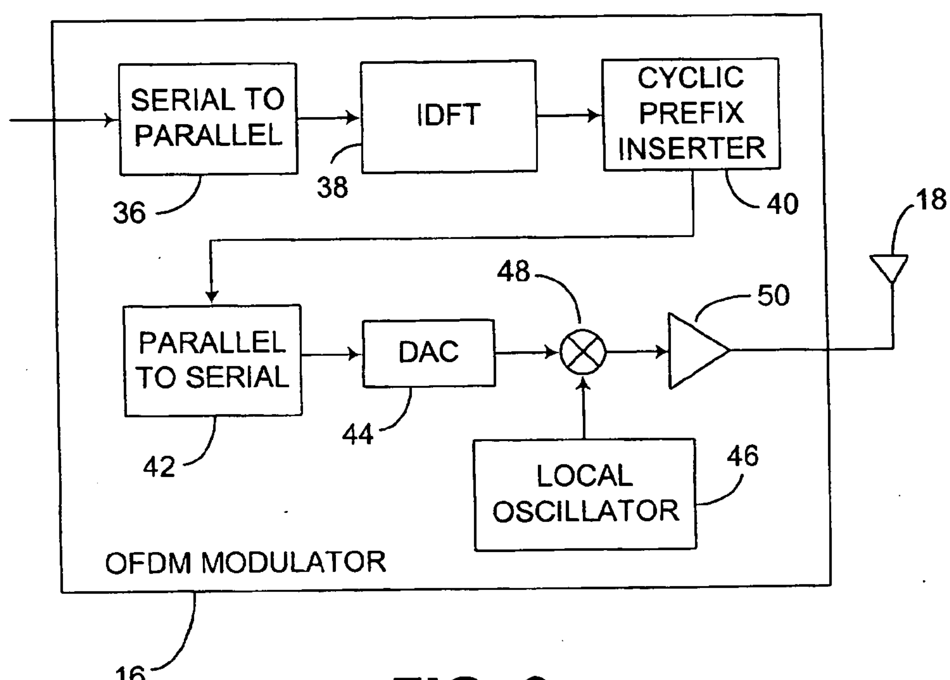

SERIAL TO PARALLEL
IDFT
CYCLIC PREFIX INSERTER
36
38
40
18
48
50
PARALLEL TO SERIAL
DAC
42
44
LOCAL OSCILLATOR
46
OFDM MODULATOR
16

FIG. 3

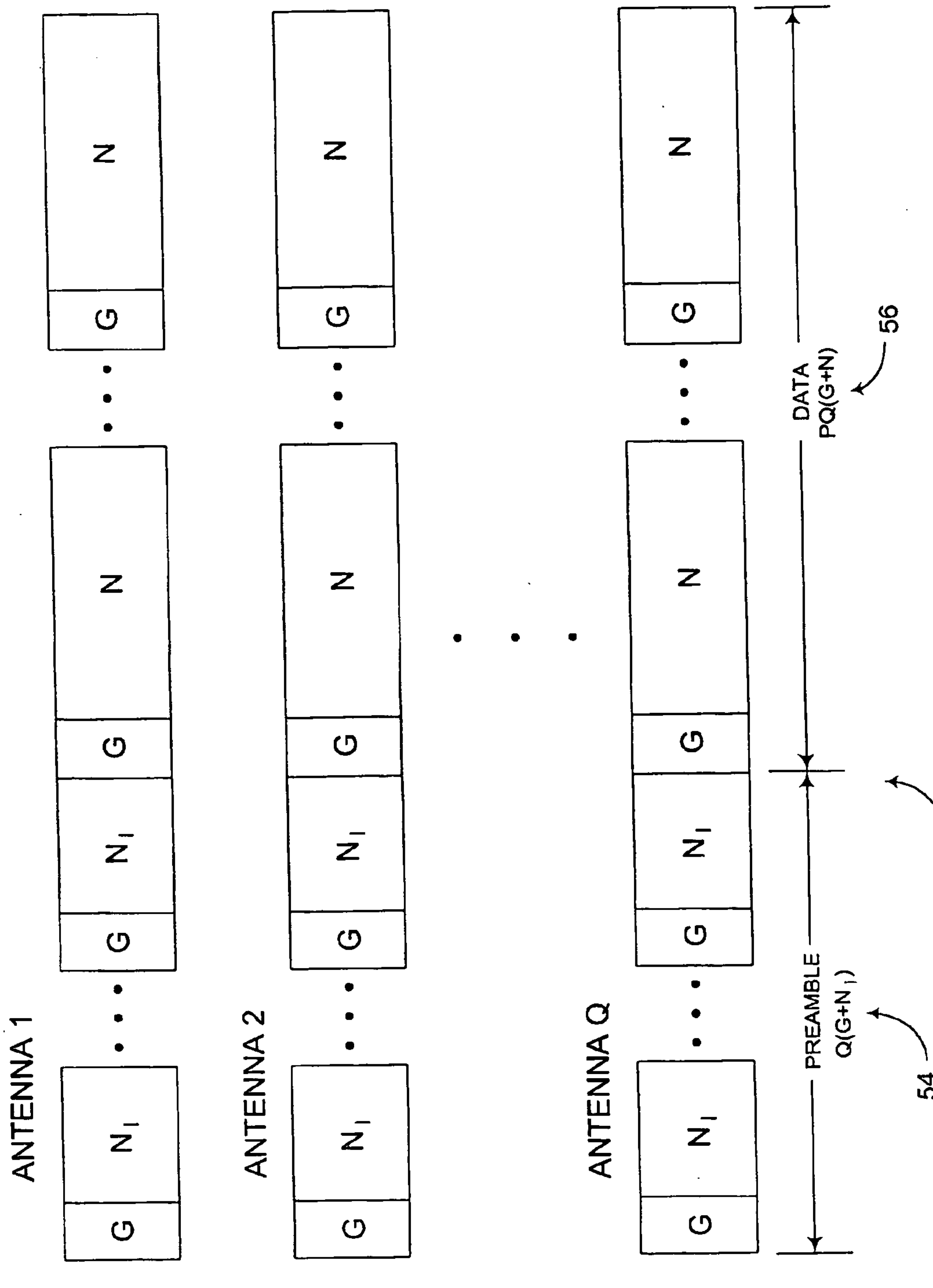

ANTENNA 1
ANTENNA 2
ANTENNA Q
G
N_I
N
DATA
PQ(G+N)
PREAMBLE
$Q(G+N_I)$
52
54
56

FIG. 4

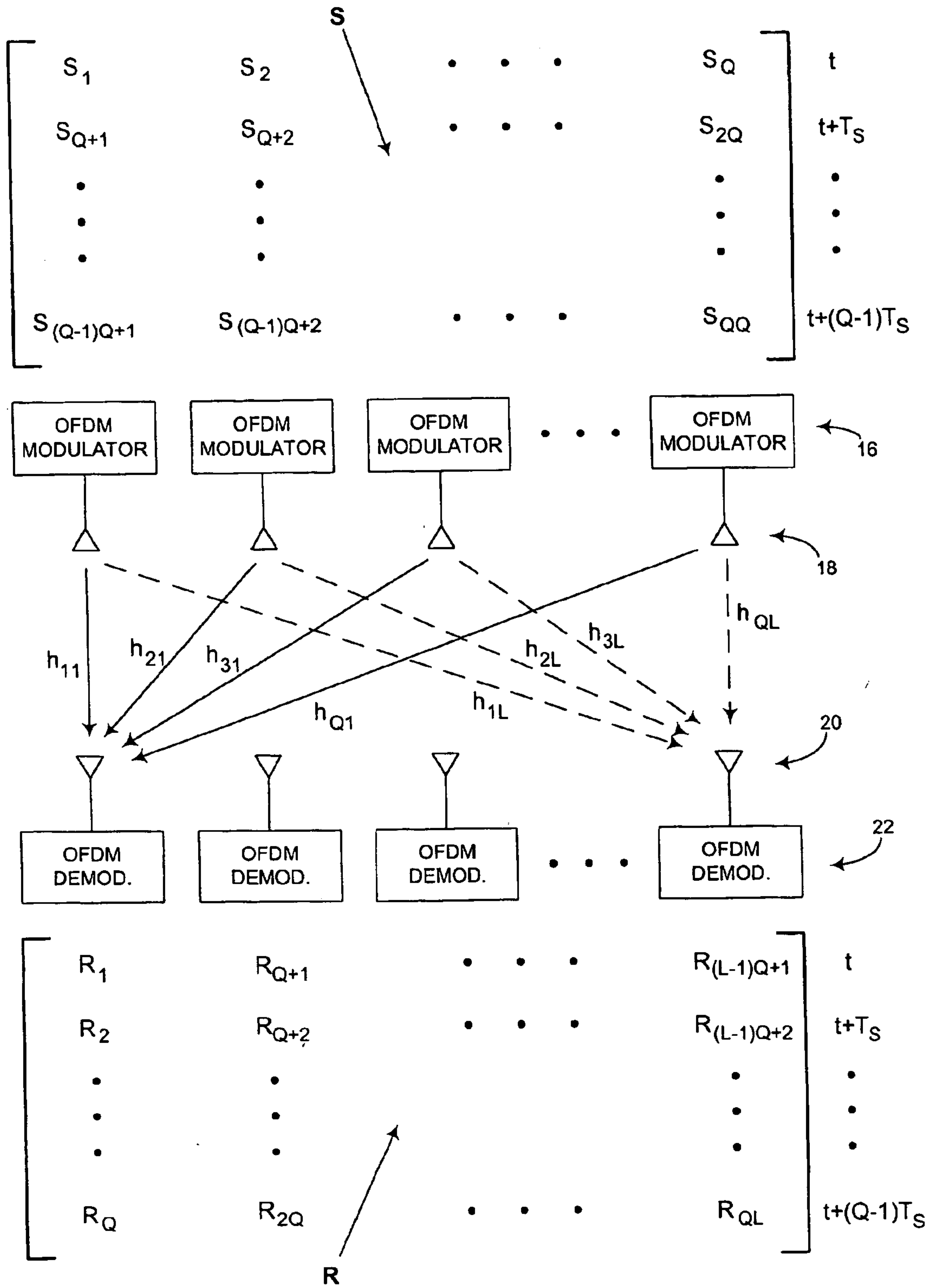

S
S_1
S_2
S_Q
t
S_{Q+1}
S_{Q+2}
S_{2Q}
$t+T_S$
$S_{(Q-1)Q+1}$
$S_{(Q-1)Q+2}$
S_{QQ}
$t+(Q-1)T_S$
OFDM MODULATOR
OFDM MODULATOR
OFDM MODULATOR
OFDM MODULATOR
16
18
h_{11}
h_{21}
h_{31}
h_{Q1}
h_{1L}
h_{2L}
h_{3L}
h_{QL}
20
22
OFDM DEMOD.
OFDM DEMOD.
OFDM DEMOD.
OFDM DEMOD.
R_1
R_{Q+1}
$R_{(L-1)Q+1}$
t
R_2
R_{Q+2}
$R_{(L-1)Q+2}$
$t+T_S$
R_Q
R_{2Q}
R_{QL}
$t+(Q-1)T_S$
R

FIG. 5

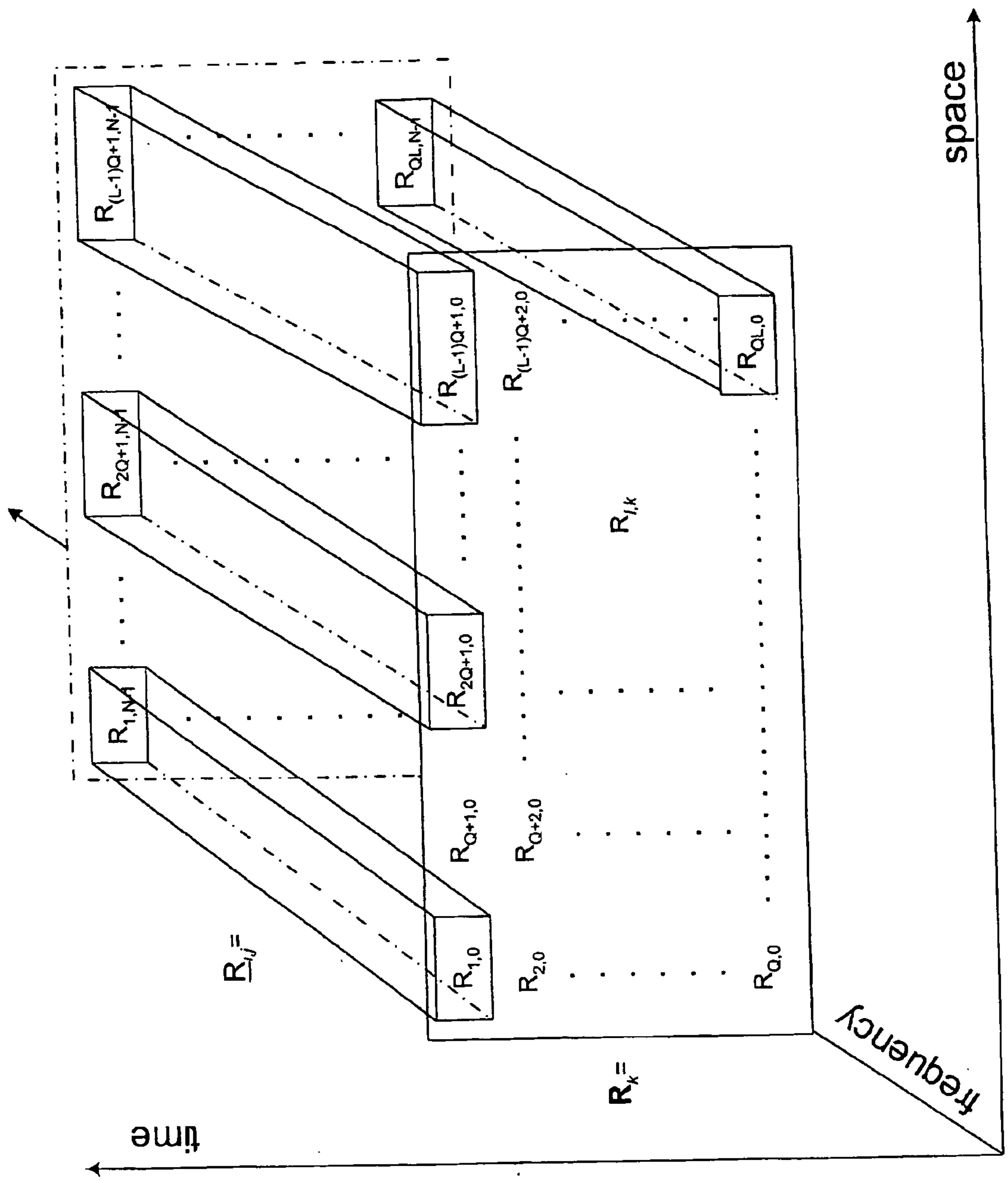

space
time
frequency
$R_{(L-1)Q+1,N-1}$
$R_{QL,N-1}$
$R_{(L-1)Q+1,0}$
$R_{(L-1)Q+2,0}$
$R_{QL,0}$
$R_{2Q+1,N-1}$
$R_{l,k}$
$R_{2Q+1,0}$
$R_{1,N-1}$
$R_{Q+1,0}$
$R_{Q+2,0}$
$R_{l,j}$=
$R_{1,0}$
$R_{2,0}$
$R_{Q,0}$
R_k=

FIG. 6

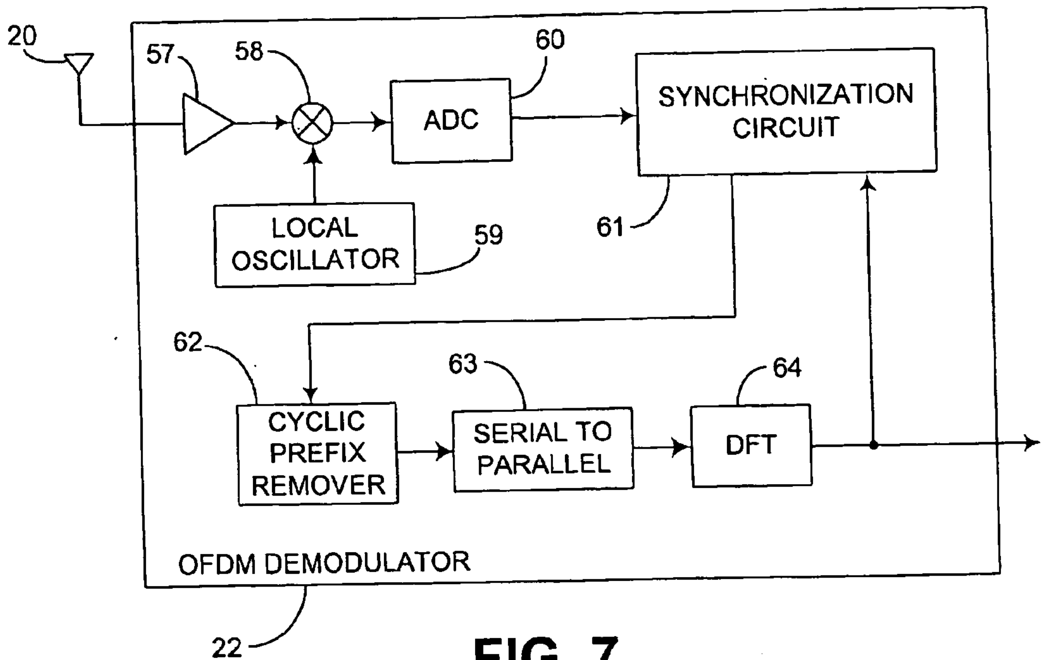


FIG. 7

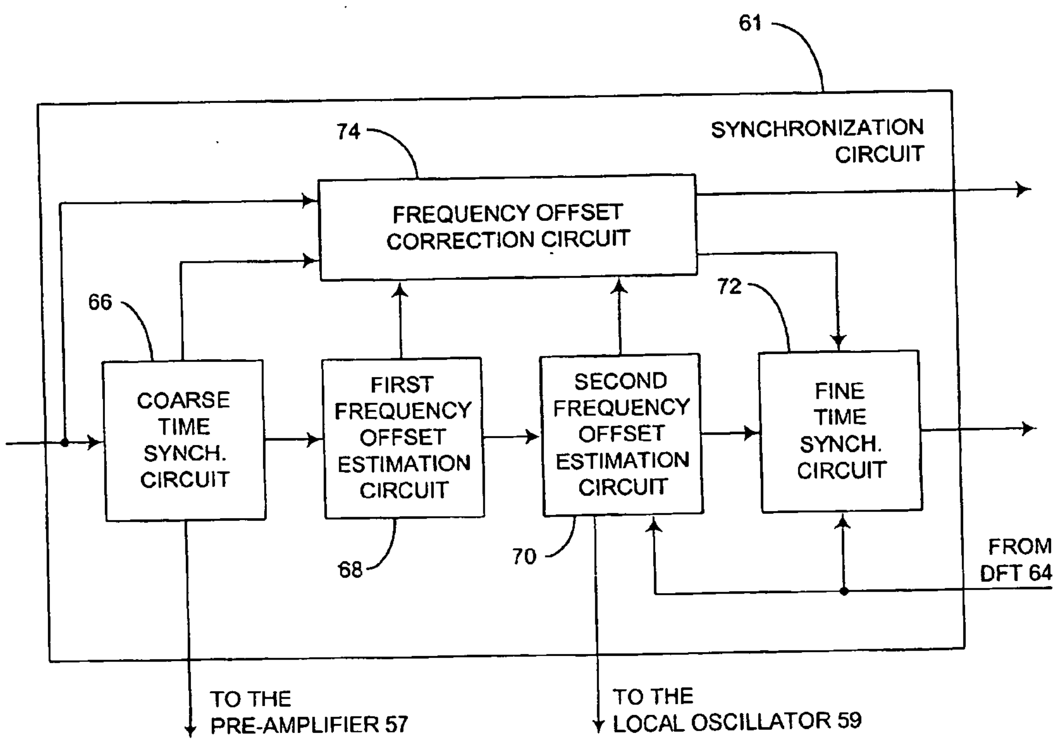


FIG. 8

2/25/05, EAST Version: 2.0.1.4

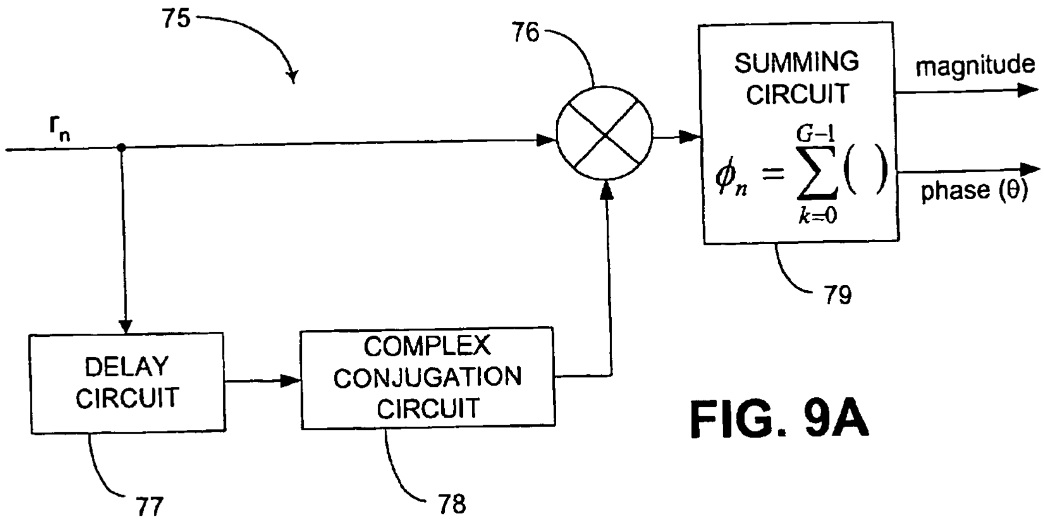


FIG. 9A

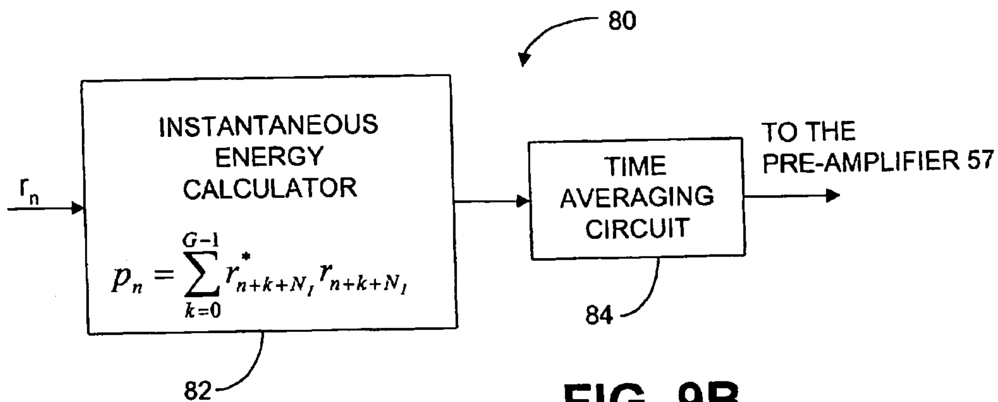


FIG. 9B

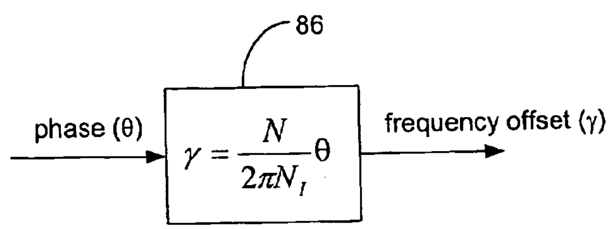


FIG. 10

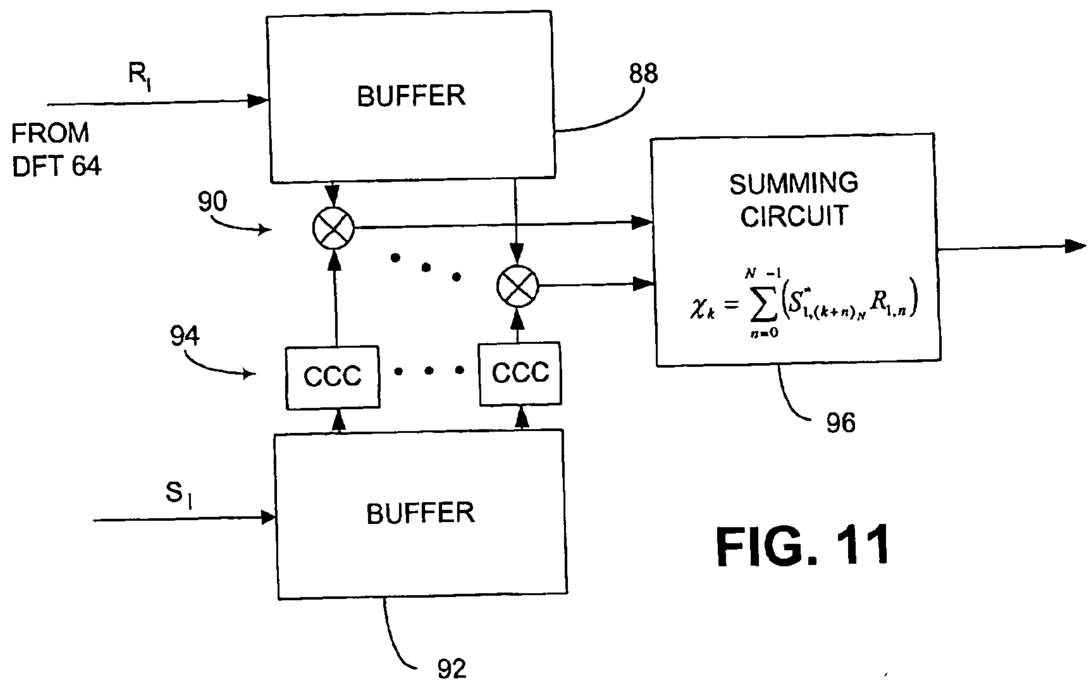

R_l
FROM
DFT 64
BUFFER
88
90
SUMMING
CIRCUIT
$\chi_k = \sum_{n=0}^{N-1}\left(S^*_{1,(k+n)_N} R_{1,n}\right)$
94
CCC
CCC
96
S_l
BUFFER
92

FIG. 11

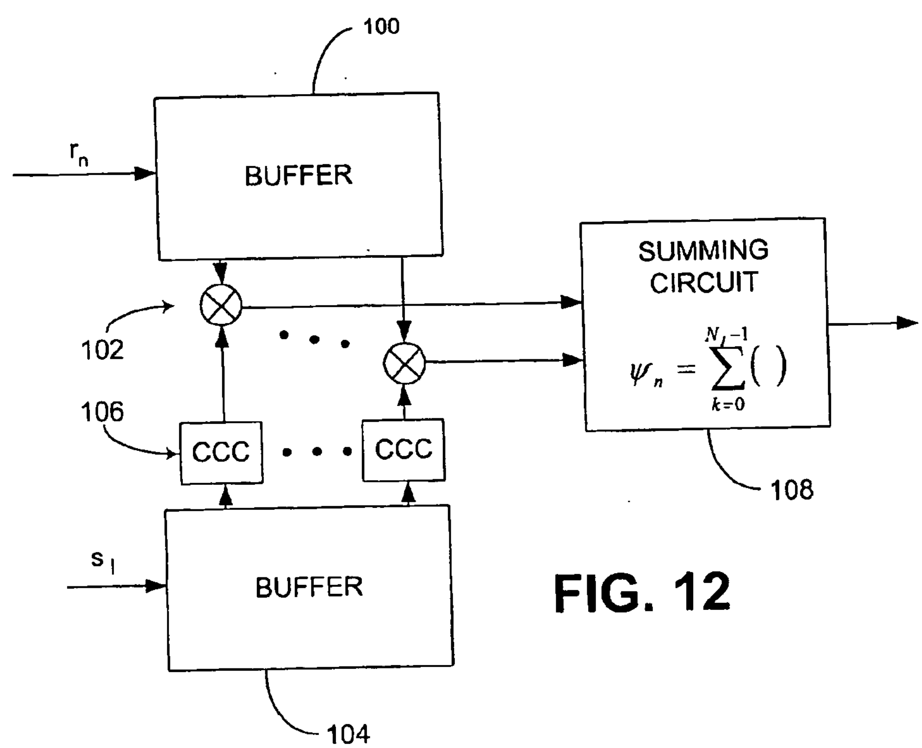

100
r_n
BUFFER
SUMMING
CIRCUIT
102
$\psi_n = \sum_{k=0}^{N_l-1}(\,)$
106
CCC
CCC
108
s_l
BUFFER
104

FIG. 12

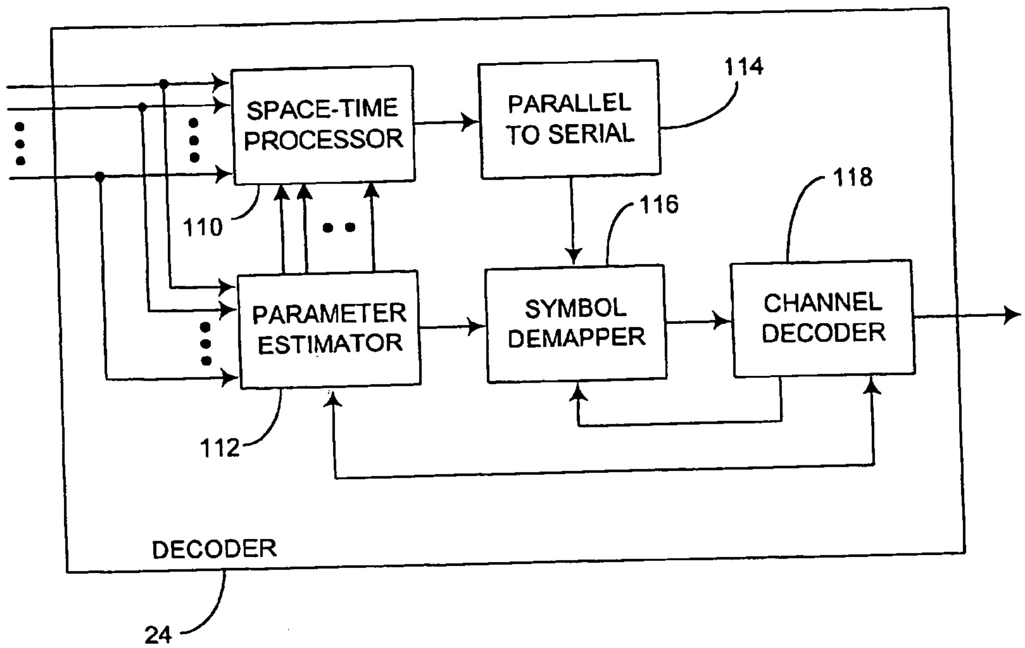

SPACE-TIME PROCESSOR
PARALLEL TO SERIAL
114
110
118
116
PARAMETER ESTIMATOR
SYMBOL DEMAPPER
CHANNEL DECODER
112
DECODER
24

FIG. 13

TIME AND FREQUENCY SYNCHRONIZATION IN MULTI-INPUT, MULTI-OUTPUT (MIMO) SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to copending U.S. provisional application entitled, "Synchronization for MIMO OFDM Systems," having serial No. 60/286,180, filed Apr. 24, 2001, which is entirely incorporated herein by reference.

[0002] This application is related to copending U.S. provisional application entitled "Parameter Estimation for MIMO OFDM Systems," having serial No. 60/286,130, filed on Apr. 24, 2001, which is entirely incorporated herein by reference.

TECHNICAL FIELD OF THE INVENTION

[0003] The present invention is generally related to wireless communication systems that employ Orthogonal Frequency Division Multiplexing (OFDM) and, more particularly, to an apparatus and method for providing time and frequency synchronization in a Multi-Input, Multi-Output (MIMO) OFDM system.

BACKGROUND OF THE INVENTION

[0004] In wireless communication systems, recent developments have been made using technologies wherein multiple signals are simultaneously transmitted over a single transmission path. In Frequency Division Multiplexing (FDM), the frequency spectrum is divided into sub-channels. Information (e.g. voice, video, audio, text, etc.) is modulated and transmitted over these sub-channels at different sub-carrier frequencies.

[0005] In Orthogonal Frequency Division Multiplexing (OFDM) schemes, the sub-carrier frequencies are spaced apart by precise frequency differences. Because of the ability of OFDM systems to overcome the multiple path effects of the channel, and to transmit and receive large amounts of information, much research has been performed to advance this technology. By using multiple transmitting antennas and multiple receiving antennas in OFDM systems, it is possible to increase the capacity of transmitted and received data while generally using the same amount of bandwidth as in a system with one transmit and one receive antenna.

[0006] OFDM technologies are typically divided into two categories. The first category is the Single-Input, Single-Output (SISO) scheme, which utilizes a single transmitting antenna to transmit radio frequency (RF) signals and a single receiving antenna to receive the RF signals. The second category is the Multi-Input, Multi-Output (MIMO) scheme, which uses multiple transmitting antennas and multiple receiving antennas.

[0007] In typical communication systems, training symbols, or preamble, at the beginning of data frames, are usually added as a prefix to the data symbols. The data symbols, of course, include the useful data or information (e.g., voice, data, video, etc.), which is meant to be transmitted to a remote location. The training symbols in SISO systems are used to provide synchronization of the received signals with respect to the transmitted signals, as well as to provide channel parameter estimation.

[0008] Although training symbols used for SISO systems can be used to provide synchronization in a MIMO system, the training symbols cannot provide for channel parameter estimation in the MIMO system. In fact, no method or apparatus exists for MIMO systems that are capable of providing time and frequency synchronization as well as channel parameter estimation. Thus, a need exists for a method and apparatus that is capable of providing time and frequency synchronization in MIMO systems and can further perform channel estimation.

SUMMARY OF THE INVENTION

[0009] The present invention provides systems and methods that overcome the deficiencies of the prior art as mentioned above. The present invention utilizes a sequence of training symbols or preambles that may be used in both Single-Input, Single-Output (SISO) and Multi-Input, Multi-Output (MIMO) systems, using any number of transmitting and receiving antennas. Also, the present invention can be used to synchronize a received data frame with a transmitted data frame in a MIMO system in both the time domain and frequency domains. In order to make MIMO systems operational, synchronization is essential. However, no scheme has been developed which is capable of time and frequency synchronization in MIMO systems. The present invention achieves synchronization in the time domain and frequency domain and, therefore, enables MIMO systems to operate acceptably.

[0010] One MIMO Orthogonal Frequency Division Multiplexing (OFDM) system of the present invention includes a number of OFDM modulators, which provide data frames to be transmitted across a channel. The data frames of the present invention comprise one or more training symbols, a plurality of data symbols, and cyclic prefixes inserted between the data symbols. A number of transmitting antennas corresponding to the number of modulators is used to transmit the modulated signals over the channel. A number of receiving antennas is used to receive the transmitted signals. The received signals are demodulated by a number of OFDM demodulators corresponding to the number of receiving antennas and decoded by an OFDM decoder, which processes the data frames. By utilizing the structure embedded in the training symbols, the MIMO system of the present invention is capable of providing time and frequency synchronization as well as perform channel estimation.

[0011] A method of the present invention is also provided, wherein synchronization is carried out in the time and frequency domains in a MIMO system. The method includes producing data frames comprising at least one training symbol, multiple data symbols and cyclic prefixes. The data frames are transmitted over the channel, received, and demodulated and processed. By processing the training symbol of the data frame, the data frame can be synchronized in both the time and frequency domains.

[0012] Other systems, methods, features, and advantages of the present invention will become apparent to a person having skill in the art upon examination of the following drawings and detailed description. All such additional systems, methods, features, and advantages are within the scope of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Many aspects of the invention can be better understood with reference to the following drawings. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0014] FIG. 1 is a block diagram illustrating an example embodiment of a Multi-Input, Multi-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) system.

[0015] FIG. 2 is a block diagram illustrating an example embodiment of the MIMO encoder shown in FIG. 1.

[0016] FIG. 3 is a block diagram illustrating an example embodiment of one of the OFDM modulators shown in FIG. 1.

[0017] FIG. 4 illustrates an example frame structure for a MIMO OFDM system.

[0018] FIG. 5 is a block diagram illustrating an example matrix of a transmitted sequence structure and an example matrix of a received sequence structure using the modulator/demodulator arrangement shown in FIG. 1.

[0019] FIG. 6 illustrates a three-dimensional representation of the received sequence structure in detail.

[0020] FIG. 7 is a block diagram illustrating an example embodiment of one of the OFDM demodulators shown in FIG. 1.

[0021] FIG. 8 is a block diagram illustrating an example embodiment of the synchronization circuit shown in FIG. 7.

[0022] FIGS. 9A and 9B are block diagrams illustrating example embodiments of the coarse time synchronization circuit shown in FIG. 8.

[0023] FIG. 10 is a block diagram illustrating an example embodiment of the first frequency offset estimation circuit shown in FIG. 8.

[0024] FIG. 11 is a block diagram illustrating an example embodiment of the fine time synchronization circuit shown in FIG. 8.

[0025] FIG. 12 is a block diagram illustrating an example embodiment of the second frequency offset estimation circuit shown in FIG. 8.

[0026] FIG. 13 is a block diagram illustrating an example embodiment of the decoder shown in FIG. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0027] In FIG. 1, an example embodiment of a Multi-Input, Multi-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) communication system 6 of the present invention is shown. The communication system 6 in this example embodiment may be implemented as a wireless system for the transmission and reception of data across a wireless channel 19. The communication system 6, for example, may be part of a wireless Local Area Network (LAN) system or wireless Metropolitan Area Network (MAN) system, cellular telephone system, or other type of radio or microwave frequency system incorporating either one-way or two-way communication over a range of distances. The communication system 6 may transmit in a range from 2 to 11 GHz, for example, such as in the unlicensed 5.8 GHz band using a bandwidth of about 3-6 MHz.

[0028] It is also possible for the present invention to be used in a system that comprises an array of sub-channel communication links that carry a number of signals transmitted by a number of transmitting elements to each of a number of receiving elements. In this latter case, communication links, such as wires in a wiring harness or some alternative wired transmission system, for example, could be used over the distance between a data source and a receiver.

[0029] In the example embodiment of FIG. 1, a transmitter 8 transmits signals across the wireless channel 19 and a receiver 10 receives the transmitted signals. The transmitter 8 comprises a data source 12, which provides the original binary data to be transmitted from the transmitter 8. The data source 12 may provide any type of data, such as, for example, voice, video, audio, text, etc. The data source 12 applies the data to an encoder 14, which encodes the data to allow for error correction. The encoder 14 further processes the data so that certain criterion for space-time processing and OFDM are satisfied. The encoder 14 separates the data onto multiple paths in the transmitter 8, each of which will hereinafter be referred to as a transmit diversity branch (TDB). The separate TDBs are input into OFDM modulators 16, each of which modulates the signal on the respective TDB for transmission by the transmitting antennas 18. The present invention may be used in a Single-Input, Single-Output (SISO) system, which may be considered as a special case of MIMO wherein the number of transmitting and receiving antennas is one. In the SISO system example, separation of the data by the encoder 14 is not necessary since only one OFDM modulator 16 and antenna 18 is used.

[0030] During the encoding by the encoder 14 and modulating by the OFDM modulators 16, data is normally bundled into groups such that the collection of each group of data is referred to as a "frame." Details of the frame as used in the present invention will be described in more detail below with reference to FIG. 4. Each frame along each TDB is output from a respective OFDM modulator 16. As illustrated in FIG. 1, any number of OFDM modulators 16 may be used. The number of OFDM modulators 16 and respective transmitting antennas 18 may be represented by a variable "Q." The OFDM modulators 16 modulate the respective frames at specific sub-carrier frequencies and respective transmitting antennas 18 transmit the modulated frames over the channel 19.

[0031] On the side of the receiver 10, a number "L" of receiving antennas 20 receives the transmitted signals, which are demodulated by a number L of respective OFDM demodulators 22. The number L may represent any number and is not necessarily the same as the number Q. In other words, the number Q of transmitting antennas 18 may be different from the number L of receiving antennas 20, or they may alternatively be the same. The outputs of the demodulators 22 are input into a decoder 24, which combines and decodes the demodulated signals. The decoder 24 outputs the original data, which may be received by a device (not shown) that uses the data.

[0032] The communication system 6 may comprise one or more processors, configured as hardware devices for executing software, particularly software stored in computer-read-

able memory. The processor can be any custom made or commercially available processor, a central processing unit (CPU), an auxiliary processor among several processors associated with a computer, a semiconductor based microprocessor (in the form of a microchip or chip set), a macroprocessor, or generally any device for executing software instructions. Examples of suitable commercially available microprocessors are as follows: a PA-RISC series microprocessor from Hewlett-Packard Company, an 80x86 or Pentium series microprocessor from Intel Corporation, a PowerPC microprocessor from IBM, a Sparc microprocessor from Sun Microsystems, Inc, a 68xxx series microprocessor from Motorola Corporation, or a 67xxx series Digital Signal Processor from the Texas Instruments Corporation.

[0033] When the communication system **6** is implemented in software, it should be noted that the communication system **6** can be stored on any computer-readable medium for use by or in connection with any computer-related system or method. In the context of this document, a computer-readable medium is an electronic, magnetic, optical, or other physical device or means that can contain or store a computer program for use by or in connection with a computer related system or method. The communication system **6** can be embodied in any computer-readable medium for use by or in connection with an instruction execution system, apparatus, or device, such as a computer-based system, processor-containing system, or other system that can fetch the instructions from the instruction execution system, apparatus, or device and execute the instructions. In the context of this document, a "computer-readable medium" can be any means that can store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device. The computer-readable medium can be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. Examples of the computer-readable medium include the following: an electrical connection having one or more wires, a portable computer diskette, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM, EEPROM, or Flash memory), an optical fiber, and a portable compact disc read-only memory (CDROM). Note that the computer-readable medium could even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via for instance optical scanning of the paper or other medium, then compiled, interpreted or otherwise processed in a suitable manner if necessary, and then stored in a computer memory.

[0034] In an alternative embodiment, where the communication system **6** is implemented in hardware, the communication system can be implemented with any or a combination of the following technologies, which are each well known in the art: one or more discrete logic circuits having logic gates for implementing logic functions upon data signals, an application specific integrated circuit (ASIC) having an appropriate combination of logic gates, a programmable gate array (PGA), a field programmable gate array (FPGA), etc.

[0035] The encoder **14** and OFDM modulators **16** of the transmitter **8** will now be described with respect to **FIGS. 2 and 3**. **FIG. 2** shows details of an example embodiment of the encoder **14** shown in **FIG. 1**. The encoder **14** may be configured such that data from the data source **12** is encoded by a channel encoder **26**, which adds parity to the original data to produce channel encoded data. The channel encoder **26** encodes the data using a scheme that is recognized by the decoder **24** of the receiver **10** and enables the decoder **24** to detect errors in the received data. Errors may arise as a result of environmental conditions of the channel **19** or noise inadvertently added by the transmitter **8** or receiver **10**.

[0036] The encoder **14** further includes a symbol mapper **28**, which maps the channel-encoded data into data symbols. The symbol mapper **28** groups a predetermined number of bits such that each group of bits constitutes a specific symbol chosen from a pre-determined alphabet. The symbol mapper **28** further lays out a stream of data symbols within the structure of a frame.

[0037] The encoder **14** further includes a space-time processor **30** that processes the data symbol stream received from the symbol mapper **28** and outputs the processed data symbols via the respective TDBs. The space-time processor **30** encodes the data symbol stream in a manner such that the receiver **10** is capable of decoding the signals. The data symbols in the TDBs are distributed over Q lines that will eventually be transmitted at precise frequencies spaced apart from each other by a predetermined difference in frequency. By providing a specific frequency difference between the multiple sub-channels, orthogonality can be maintained, thereby preventing the OFDM demodulators 22 from picking up frequencies other than their own designated frequency.

[0038] Each TDB provides an input to a respective adder **34**. The other input into each of the adders **34** is connected to the output of a pilot/training symbol inserter **32**, which provides pilot symbols and training symbols to be inserted into the frames on the TDBs. Symbols inserted periodically within the data symbols will be referred to herein as "pilot symbols." These periodic pilot symbols may be inserted anywhere in the stream of the data symbols. If a continuous burst of symbols is inserted by the pilot/training symbol inserter **32**, this type of symbol will be referred to herein as "training symbols" which constitute the preamble. The training symbols preferably are inserted at the beginning of the frame. However, the training symbols may be inserted onto the frame in a location other than at the beginning of the frame, such as at the end or in the middle of the frame.

[0039] The pilot/training symbol inserter **32** may be configured so that it is capable of storing multiple sets of training symbols or pilot symbols. In this case, a particular set may be selected, for example, based on desirable communication criteria established by a user. The training symbols for each respective sub-channel may preferably be unique to the particular sub-channel. In order to accommodate amplitude differences between the sub-channels, the training symbols may be designed and adjusted to maintain a constant amplitude at the output of each sub-channel.

[0040] Training symbols are preferably transmitted once for every frame. Training symbols are used for periodic calibration (synchronization and channel parameter estimation) whereas pilot symbols are used for minor adjustments to deal with the time-varying nature of the channel. The training symbols may be indicative of calibration values or known data values. These calibration values or known

values may be transmitted across the channel, and used to calibrate the communication system **6**. Any necessary refinements may be made to the communication system **6** if the received calibration values do not meet desirable specifications.

[0041] Furthermore, the training symbols may be used as specific types of calibration values for calibrating particular channel parameters. By initially estimating these channel parameters, offsets in the time domain and frequency domain may be accounted for so as to calibrate the communication system **6**. The training sequence may or may not bypass an Inverse Discrete Fourier Transform (IDFT) stage **38**, which is a part of the embodiment of the OFDM modulator **16** of **FIG. 3**. A training sequence that bypasses the IDFT stage **38** and is directly input into a digital to analog converter (DAC) **44** is referred to herein as a directly modulatable training sequence. Examples of such training sequences may be "chirp-like" sequences. These sequences cover each portion of the bandwidth used by the communication system **6**. Hence, channel response can be easily determined. In general, a chirp sequence in the time domain is given by the equation:

$$S_n = \cos(\pi n/N^2) + j\sin(\pi n^2/N),\ n=0,1,\ \ldots,\ N-1,$$

[0042] where j is given by $\sqrt{-1}$ and is used to denote the quadrature component of the signal. It should be noted that the term s_n refers to a time domain signal on the side of the transmitter **8**. Frequency domain signals on the transmitter side will hereinafter be referenced by capital letters S_k. Time and frequency domain signals on the receiver side will hereinafter be written as r_n and R_k, respectively. Other modifications of the chirp-like sequence may be Frank-Zadoff sequences, Chu sequences, Milewski sequences, Suehiro polyphase sequences, and sequences given by Ng et al. By observing the response of the receiver **10** to the chirp signals, the channel parameters maybe estimated.

[0043] In the case when the IDFT stage **38** is not bypassed, a training sequence may be generated by modulating each of the symbols on the TDBs with a known sequence of symbols in the frequency domain and passing the symbols through the IDFT stage **38**. Generally, such a known sequence of symbols is obtained from an alphabet which has its constituents on the unit circle in the complex domain and such that the resultant sequence in the time domain has a suitable Peak to Average Power Ratio (PAPR). An alphabet in communication systems is defined as a finite set of complex values that each of the symbols can assume. For example, an alphabet of a binary phase shift keying (BPSK) system consists of values +1 and −1 only. An alphabet for a quaternary phase shift keying (QPSK) system consists of the values 1+j, −1+j, 1−j, and −1−j. For example, the training sequence may be generated by modulating each of the tones of the OFDM block using a BPSK alphabet, which consists of symbols +1 and −1. The synchronization scheme may be very general such that any known sequence having suitable properties, such as low PAPR, may be used to form the training sequence.

suitable properties!

[0044] With reference again to **FIG. 2**, the adders **34** add the training symbols and pilot symbols to the frame. Other embodiments may be used in place of the adders **34** for combining the training symbols and pilot symbols with the data symbols in the frame. Furthermore, the adders **34** may include additional inputs to allow for flexibility when adding the pilot/training symbols or in the combining of multiple training symbols or even selectable training symbols. After the training symbols are inserted into frames on the respective TDBs, the frames are output from the encoder **14** and input in respective OFDM modulators **16**.

[0045] **FIG. 3** shows an example embodiment of an OFDM modulator **16**, which receives signals along one of the TDBs. The number of OFDM modulators **16** is preferably equal to the number of transmitting antennas **18**. In SISO systems, there is only one OFDM modulator **16** and one transmitting antenna **18**. In MIMO systems, there may be any number of OFDM modulators **16** and transmitting antennas **18**.

[0046] The respective signal from the encoder **14** is input into a serial-to-parallel converter **36** of the OFDM modulator **16**. The serial-to-parallel converter **36** takes N symbols received in a serial format and converts them into a parallel format. The variable N will be referred to herein as the blocksize of the OFDM symbol. The N parallel symbols are processed by an Inverse Discrete Fourier Transform (IDFT) stage **38**, which transforms the frequency signals to the time domain. The N number of transformed symbols in the time domain will be referred to herein as samples.

[0047] A method is proposed herein to design the training symbols such that the transforms of all the sequences from the IDFT stage **38** will have a constant magnitude. By maintaining a constant magnitude at the output of each of the IDFT stages **38** within their respective modulators, one of the main problems of OFDM, i.e., peak to average power ratio (PAPR), is solved. The receiver **10** can thus more accurately estimate the channel parameters, which are used by the receiver **10** to synchronize the received signals in the time and frequency domains, as will be described below in more detail.

[0048] The output from the IDFT stage **38** is input into a cyclic prefix inserter **40**, which inserts an additional number of samples for every N samples. The number of samples inserted by the cyclic prefix inserter **40** will be referred to herein by the variable "G." The G samples are intended to be inserted as guard intervals to separate the N adjacent data symbols from each other in time by a separation adequate to substantially eliminate Inter Symbol Interference (ISI). The cyclic prefix inserter **40** repeats G samples from a latter portion of the N samples output from the IDFT stage **38** and inserts the G samples as a prefix to each of the data samples. Preferably, the time length of the cyclic prefix is greater than the maximum time delay of a transmitted signal across the channel **19**. Since the nature of the channel **19** may be susceptible to a variation in the delay time from the transmitted antennas **18** to the receiving antennas **20**, it may be desirable to increase, or even double, the length of cyclic prefixes of the preamble to ensure that the time delay of the channel does not exceed the time of the cyclic prefix, thereby eliminating ISI.

[0049] The G+N samples, herein referred to as an OFDM symbol, are then converted from a parallel format to a serial format using parallel-to-serial converter **42**, and then inputted to a digital-to-analog converter (DAC) **44** for conversion into analog signals. The output from the DAC **44** is input into a mixer **48**. A local oscillator **46** provides a signal having the carrier frequency to the other input of the mixer **48** to up-convert the respective OFDM symbol from baseband to RF.

[0050] After the respective frame has been mixed with a carrier frequency that is set by the respective local oscillator **46**, the frame is amplified by an amplifier **50**. As indicated above, one of the drawbacks to any OFDM signal is that it generally has a high PAPR. To accommodate this drawback, the amplifier **50** may be backed off to prevent it from going into its non-linear region. However, the present invention may provide certain specific sequences that can be used in order to make the PAPR minimal or unity.

[0051] Each OFDM modulator **16** preferably comprises the same components as the OFDM modulator **16** shown in **FIG. 3**. Other techniques for designing the OFDM modulators **16** may be used in order to transmit the multiple frames across the channel **19** with minimal interference. Each frame output from the respective OFDM modulator **16** is transmitted by a respective antenna **18**. The antennas **18** may be spaced apart from each other by any desirable separation. For example, the separation distance may be in a range from a few millimeters to several meters.

[0052] **FIG. 4** illustrates an example of a frame **52** that is transmitted across the channel **19** from the transmitting antennas **18** to the receiving antennas **20**. The frame **52** comprises a preamble **54** comprising a number of training symbols N_I and cyclic prefixes G. The preamble **54** is inserted by the pilot/training symbol inserter **32** as mentioned above. In addition, the data frame **52** comprises a data portion **56** consisting of a plurality of OFDM data symbols N and cyclic prefixes G, which are inserted before each of the OFDM data symbols N. As previously mentioned, the pilot/training symbol inserter **32** further inserts pilot symbols (not shown) intermittently within the OFDM data symbols N. The task of the preamble **54** and training symbols N_I in the frame is to help the receiver **10** identify the arrival of the frame **52** and hence perform time synchronization, frequency synchronization, and channel parameter estimation.

[0053] The preamble **54**, in general, consists of Q or more training symbols, wherein each training symbol has a length of $G+N_I$ samples in time. The number of samples N_I is established as a certain fraction of the number of data samples N in an OFDM block such that $N_I=N/I$, where I is an integer, such as 1, 2, 4 . . . . For example, N_I may be ¼ N. If no predetermined N_I has been established, the variable N_I may be given the value equal to N. The training symbol length may be shorter than the length of the symbols in the data portion **56**, which has a length of G+N samples.

[0054] **FIG. 5** shows a portion of the MIMO OFDM communication system **6** of **FIG. 1** along with details of a signal transmission matrix S and a received demodulated OFDM sample matrix R. The signals of the communication system **6** can be expressed using the equation:

$$R_{k,T\times L}=S_{k,T\times Q}\eta_{k,Q\times L}+W_{k,T\times L}$$

[0055] where R is a T×L received demodulated OFDM sample matrix, η is a Q×L matrix of channel coefficients that are indicative of the characteristics of the channel across which the signals are transmitted, S is a T×Q signal transmission matrix, and W is a T×L noise matrix that corrupts and distorts the received sample matrix R. In general, T may or may not be equal to Q and does not affect the synchronization procedure. Hence, for simplicity, the assumption is made herein that T is equal to Q.

[0056] The signal transmission matrix S shown in **FIG. 5** consists of Q OFDM symbols that are simultaneously transmitted from Q transmit antennas **18** over Q or more OFDM symbol periods (T_s). For example, at a first time instance t, the OFDM symbols $S_1, S_2, \ldots S_Q$ are transmitted from the first to the Qth antennas **18**. At a second time instance $t+T_S$, the OFDM symbols $S_{Q+1}, S_{Q+2}, \ldots S_{2Q}$ are transmitted from the same antennas **18**. The OFDM symbol transmissions are repeated at each time instance until all of the OFDM symbols of the matrix S have been transmitted.

[0057] During the transmission of training symbols in an initial calibration mode, the S matrix consists of Q or more training symbols, each of which is less than or equal to the length of an OFDM symbol in the time dimension. The training symbols are simultaneously transmitted from the transmitting antennas **18** as represented by equations (1) and (2), wherein the different antennas correspond to the space dimension.

[0058] During the transmission of the data symbols, after the communication system **6** has been calibrated, the S matrix consists of Q or more data symbols each occupying an OFDM symbol in the time dimension. The pilot/training symbol inserter **32** inserts the pilot symbols within the data symbols. The data symbols are encoded, modulated, and transmitted from the transmitting antennas **18**.

[0059] Each signal transmission matrix S of Q×Q OFDM symbols are transmitted over the communication channel **19**, which naturally comprises a matrix of channel coefficients η. Typically, the communication channel **19** includes characteristics that distort and degrade the transmitted signal. In addition to the distortion and degradation of the transmitted signal, the communication system adds noise terms represented by the matrix W, before the signal transmission matrix S is received at the L receive antennas **20**. The addition of noise further degrades the system performance.

[0060] **FIG. 5** further illustrates how each of the L receiving antennas **20** receives each of the Q transmitted signals. For example, the first receive antenna **20** receives OFDM signals over channel impulse responses $h_{11}, h_{21}, h_{13} \ldots h_{Q1}$ from the first to the Qth transmitting antennas **18**, respectively. The term $h_{1,J}$ refers to the channel impulse response from the i^{th} transmit to the j^{th} receive antenna in the time domain. The last receive antenna **20** receives the transmitted signals over the channel impulse responses $h_{1L}, h_{2L}, h_{3L}, \ldots h_{QL}$ from the first to the Qth transmitting antennas **18**, respectively. For simplicity, only the signals received at the first and last receiving antennas **20** are shown. However, it should be understood that each receiving antenna **20** receives the signals transmitted from the Q transmitting antennas **18**.

[0061] The received signals are demodulated by the respective OFDM demodulators **22**, which provide the received demodulated OFDM sample matrix R. At a time instance t, the samples $R_1, R_{Q+1}, \ldots R_{L-1)Q+1}$ are received. At a next time instance t+Ts, the samples $R_2, R_{Q+2} \ldots R_{(L-1)Q+2}$ are received. The samples are received at each time instance until all of the samples in the received demodulated OFDM sample matrix R are received. It should be noted that the time instances used for the matrices S and R are given the same variable, but, in essence, a delay occurs as is well known in the art.

[0062] A significant task of the receiver **10** is to estimate the time of arrival of the transmitted signal. This process is called "time synchronization." In addition to time synchronization, OFDM systems typically require frequency synchronization as well. Because there usually exists a certain difference between the local oscillator frequencies of the transmitter and the receiver, the received signals experience a loss of sub-carrier orthogonality, which should typically be corrected in order to avoid degradation in system performance.

[0063] **FIG. 6** shows a detailed illustration of the received demodulated OFDM sample matrix R which consists of L columns and Q or more rows of OFDM symbols with respect to space and time, respectively. As shown, the matrix R consists of three dimensions, namely space, time and frequency. The frequency axis indicates the amplitude of the frequency component received at each receiving antenna **20** from each transmitting antenna **18**. Each of the matrices R and η can be seen to consist of N matrices of dimension Q×L or Q×L vectors of length N.

[0064] In general, the training symbol length may be equal to the data symbol length. However, it is not necessary for the length of the training symbol in the preamble to be (N+G) since it is possible to estimate the characteristics of the channel even if the training symbol length is shortened to N_I+G such that (N_I+G)<(N+G). The variable N_I may be set so as to establish a range of frequencies that may be estimated. For example, if N_I=N/4, then a frequency offset of 4 sub-carrier spacings can be estimated using the training symbol. However, the range to be established may depend upon the characteristics of the channel to be estimated also.

[0065] Transmission of the training sequence of length N_I corresponds to exciting every Ith sub-channel of an OFDM signal having a block size N. This means that no information is transmitted on the remaining (1−1/I)N sub-channels and the estimates of the channel for the sub-channels are derived from the ones that actually include information. This may result in a poor performance and hence it is left to the system designer to determine the length of the preamble.

[0066] The sub-channels of the transmit sequence that bear no information are said to be zero-padded. Alternatively, the training sequence of length N_I may be generated by first modulating every Ith sub-channel of the OFDM block by a known sequence of symbols and zero padding the rest. An N-point IDFT is taken to obtain N samples in the time domain, and finally only the first N_I samples along with its cyclic prefix are transmitted. At the receiver after synchronization, the samples corresponding to the training sequence of length N_I are repeated I times before being demodulated by the OFDM demodulators. In a number of alternative systems, many more sub-channels are zero padded to reduce the interference between the adjacent bands and to facilitate the system implementation. For example, in the systems based on the IEEE 802.16a/b standard, a total of 56 tones or sub-carriers are zero padded.

[0067] The training sequence structure in the frequency domain is represented by its signal transmission matrix, which is configured in such a way so as to have certain properties that aid in synchronization and channel estimation. For example, the signal transmission matrix for a 2×2 system may be of the form:

$$S_k = \begin{bmatrix} S_{1,k} & S_{1,k} \\ -S_{1,k}^* & S_{1,k}^* \end{bmatrix}, \tag{1}$$

[0068] where * denotes a complex conjugate operation, and k is a sub-carrier or sub-channel index. The signal transmission matrix S for a 4×4 system may be of the form:

$$S_k = \begin{bmatrix} S_{1,k} & S_{1,k} & S_{1,k} & S_{1,k} \\ -S_{1,k} & S_{1,k} & -S_{1,k} & S_{1,k} \\ -S_{1,k} & S_{1,k} & S_{1,k} & -S_{1,k} \\ -S_{1,k} & -S_{1,k} & S_{1,k} & S_{1,k} \end{bmatrix}, \tag{2}$$

[0069] where S_1 is the sequence in the frequency domain that has certain properties that satisfy the system requirements. Similarly, the signal transmission matrix S for a 3×3 system may be of the form:

$$S_k = \begin{bmatrix} S_{1,k} & S_{2,k} & \frac{S_{3,k}}{\sqrt{2}} \\ -S_{2,k}^* & S_{1,k}^* & \frac{S_{3,k}}{\sqrt{2}} \\ \frac{S_{3,k}^*}{\sqrt{2}} & \frac{S_{3,k}^*}{\sqrt{2}} & \frac{-S_{1,k} - S_{1,k}^* + S_{2,k} - S_{2,k}^*}{2} \\ \frac{S_{3,k}^*}{\sqrt{2}} & \frac{-S_{3,k}^*}{\sqrt{2}} & \frac{S_{2,k} + S_{2,k}^* + S_{1,k} - S_{1,k}^*}{2} \end{bmatrix}, \tag{3}$$

[0070] where k=0,1, . . . , N−1. The rows of the signal transmission matrix represent the time dimension, the columns represent the space dimension and the index k represents the frequency dimension or the corresponding subcarrier. The transmitter **8** may create the matrix S_k such that it is unitary. If the vectors of the training sequences are derived from the points along the unit circle in the complex domain then the signal transmission matrices S_k shown in (1) and (2) are unitary. Besides making each of the transmission matrices S_k unitary, it also facilitates the system implementation and maintains a low PAPR of the sequence structure in the time domain. This is because the signal transmission matrices in the training mode and the data mode are exactly alike, which further simplifies the system implementation. The transmission of a unitary matrix aids in parameter estimation, as is described below.

[0071] With reference again to **FIG. 1**, the L number of receiving antennas **20** receive the Q number of transmitted signals and provide the received signals to respective OFDM demodulators **22**, which down-convert the signal back to baseband. The L number of receiving antennas **20** are separated by a distance such that the received signals have minimum correlation and are as independent from each other as possible. The outputs from the L number of OFDM demodulators **22** are input into a decoder **24**, which combines the multiple signals and decodes them. In addition, the decoder **24** removes any correctable noise and distortion errors, as will be described below, and outputs signals representative of the original data.

[0072] FIG. 7 illustrates an example embodiment of one of the OFDM demodulators 22 of the receiver 10. Received signals from the receiving antenna 20 are input into a pre-amplifier 57, which amplifies the received signals to a level at which further processing may be performed. The output of the pre-amplifier 57 is connected to a mixer 58. A local oscillator 59 provides a signal to the mixer 58 having a frequency designed to demodulate the received amplified signal. The demodulated signal is then output to an analog-to-digital converter (ADC) 60, which converts the analog signals into discrete time samples. The discrete time samples are applied to a synchronization circuit 61.

[0073] An explanation will now be made to emphasize the significance of synchronization in an OFDM system. OFDM typically requires substantial synchronization in time as well as in frequency in order that transmitted signals can be recovered with adequate accuracy. Time synchronization involves determining the best possible time for the start of the received frame to closely match the start of the transmitted signal.

[0074] Frequency synchronization involves maintaining orthogonality of the respective sub-carrier frequencies. Orthogonality refers to a condition of the sub-carrier frequencies wherein the "inner product" of the signals at different sub-carrier frequencies is zero. With respect to the inner product, reference is made, for example, to the time domain sequences s ,n wherein n=0, 1, . . . N−1 and the sub-carrier index k is equal to 1. When the sub-carrier index k is equal to 2, the time domain sequences $S_{2,n}$ are transmitted. The inner product is equal to $\Sigma(s_{1,n})^*(S_{2,n})$ wherein n=0, 1, . . . N−1. When the inner product is not equal to zero, a loss of sub-channel orthogonality may result, thereby causing Inter Carrier Interference (ICI). Since the sub-channels are separated by a precise frequency difference to maintain orthogonality, any difference in frequencies between the transmitter and the receiver local oscillators may cause a loss of sub-channel orthogonality. The synchronization circuit 61 corrects this loss of sub-channel orthogonality by finding an estimate of the difference between the frequencies of the local oscillators 46 of the transmitter 8 and the frequencies of the local oscillators 59 of the receiver 10. The synchronization circuit 61 further corrects these frequency difference estimates.

[0075] The synchronization circuit 61 will now be explained with reference to FIG. 8. The input to the synchronization circuit 61, connected to the output of the ADC 60, is input into a coarse time synchronization circuit 66 and a frequency offset correction circuit 74. The coarse time synchronization circuit 66 determines the approximate start time of each received block of N+G samples by estimating the approximate starting time of the OFDM frame. The coarse time synchronization circuit 66 sends the coarsely synchronized signals to a first frequency offset estimation circuit 68. The coarse time synchronization circuit 66 sends a second output to the frequency offset correction circuit 74 and a third output back to the pre-amplifier 57 for altering the gain of the pre-amplifier 57.

[0076] The first frequency offset estimation circuit 68 estimates the frequency offset to within one-half of the sub-carrier spacings. An output from the first frequency offset estimation circuit 68 is sent to the frequency offset correction circuit 74. At this stage, the frequency offset correction circuit 74 performs an initial correction of the frequency offset, utilizing the signals received from the ADC 60, coarse time synchronization circuit 66, and the first frequency offset estimation circuit 68. The frequency offset correction circuit 74 sends the initial frequency corrected samples to a cyclic prefix remover 62, which is shown in FIG. 7. The cyclic prefix remover 62 removes the cyclic prefixes from the frames and sends the symbols, with the cyclic prefixes removed, to a serial-to-parallel converter 63. The serial-to-parallel converter 63 converts the serial stream to a parallel format and sends the parallel data to a Discrete Fourier Transform (DFT) stage 64. The DFT stage 64 converts the time domain samples to the frequency domain, and returns an output to the synchronization circuit 61 to refine the synchronization in the time and frequency domain.

[0077] With reference again to FIG. 8, the output from the DFT 64 travels to a second frequency offset estimation circuit 70 and a fine time synchronization circuit 72. The second frequency offset estimation circuit 70 receives the estimation of the frequency offset to within one-half the sub-carrier spacing form the first frequency offset estimation circuit 68 and the frequency domain samples from the DFT 64. Using these input signals, the second frequency offset estimation circuit 70 provides an estimation of the frequency offset to an integer multiple of sub-carrier spacings.

[0078] The second frequency offset estimation circuit 70 provides an output to the local oscillator 59 for adjusting the frequency of the local oscillator 59 to the frequency of the local oscillator 46 of the transmitter 8. The second frequency offset estimation circuit 70 sends a second output to the frequency offset correction circuit 74, which may further correct the frequency offset during a second stage, based on the offset estimated by the second frequency offset estimation circuit 70. Both the frequency offset correction circuit 74 and the second frequency offset estimation circuit 70 send outputs to the fine time synchronization circuit 72, which calculates a more accurate start time of the received frame. Outputs from the frequency offset correction circuit 74 and fine time synchronization circuit 72 are sent to the cyclic prefix remover 62, which receives the signals that are further synchronized during the second stage of the synchronization circuit 61.

[0079] The synchronization circuit 61 may be utilized as many times as necessary to accurately synchronize the receiver 10 in the time and frequency domains. The known calibration values may be transmitted by the transmitter 8 for an amount of time until the synchronization circuit 61 has developed an accurate correction to compensate for time variations and frequency offsets that may be inherent in the communication system 6 and channel 19. Once adequate synchronization has been obtained, frames carrying the user's data symbols may be transmitted with confidence that time and frequency synchronization will allow acceptable reception of the transmitted signals. With synchronization maintained, newly received symbols sent to the synchronization circuit 61 may bypass the synchronization and estimation circuits and pass through the frequency offset correction circuit 74 to synchronize the new symbols. Therefore, as time passes, the synchronization circuit 61 may make slight adjustments to account for any changes in the communication system 6, but may reach a steady state when the communication system 6 does not change.

[0080] The individual circuits of the synchronization circuit **61** will now be explained with reference to **FIGS. 9A, 9B, 10, 11** and **12**. The coarse time synchronization circuit **66** determines the approximate start time of each received block of N+G samples. The coarse time synchronization circuit **66** may use circuitry which takes into account the periodicity inserted into the training symbol, or in other words, the periodic occurrences of the inserted cyclic prefixes in the data frame. The coarse time synchronization circuit **66** detects the location of the cyclic prefixes by observing the repetitious nature of the G samples. To reiterate, the G samples repeat a portion of the N samples, as explained above.

[0081] The coarse time synchronization circuit **66** may comprise circuitry capable of performing a technique that is hereinafter referred to as "auto-correlation." The phase output from the auto-correlation circuit may be used in the example embodiment of the first frequency offset estimation circuit **68**, as is described in more detail below. The technique of auto-correlation is accomplished by comparing the samples of a data stream with samples of the same data stream that are delayed by the number of samples N_I.

[0082] An example embodiment of an auto-correlation circuit **75** is shown in **FIG. 9A**. A received frame is demodulated into a data stream r_n, which is input into a mixer **76** and a delay circuit **77**. The delay circuit **77** delays the data stream by N_I samples such that a second input into the mixer **76** will be offset by N_I samples. The delayed data stream is processed by a complex conjugation circuit **78**, which outputs the processed data stream to the second input of the mixer **76**.

[0083] The mixer **76** compares the data stream r_n with the delayed and processed data stream. Since the delayed data stream is delayed by N_I samples, the mixer compares the start of the preamble at the first G sample with a sample that is delayed N_I from the start of the preamble. If the comparison between the data stream r_n and the delayed data stream reveals an alignment of the G samples of the cyclic prefix with the last G samples of the training symbol N_I, then the mixer **76** outputs a constructively added waveform. The output of the mixer **76** is input into a summing circuit **79**, which sums the output of the mixer **76** over G samples and provides the magnitude and phase of the sum. The auto-correlation operation can be represented using the equation:

$$\phi_n = \sum_{k=0}^{G-1} r_{n+k}^{*} \cdot r_{n+k+N_I}$$

[0084] where the coarse time synchronization is achieved when ϕ_n attains a certain threshold value.

[0085] In addition to auto-correlation, the coarse time synchronization circuit **66** may also correct any undesirable fluctuations in the amplitude of the signals received by the receiver **10**. Signals experiencing long-term amplitude fluctuations may be corrected by an automatic gain control (AGC) circuit, which may be part of the coarse time synchronization circuit **66**. The AGC circuit may detect variations in the signal amplitudes and provide feedback signals to the pre-amplifier **57** in order to maintain the received signals at a constant magnitude.

[0086] As shown in **FIG. 9B**, an embodiment of an AGC circuit **80** comprises an instantaneous energy calculator **82**, which calculates the instantaneous energy using the formula:

$$p_n = \sum_{k=0}^{G-1} r_{n+k+N_I}^{*} r_{n+k+N_I}$$

[0087] An average of this instantaneous energy is taken over a period of time by a time averaging circuit **84** and given to the pre-amplifier **57** to correct the long term fluctuations in the amplitude of the received signal. The time averaging circuit can be represented using a formula such as:

$$P_{avg} = \frac{1}{M} \sum_{n=1}^{M} P_n,$$

[0088] where M can be any number large enough to average long term fluctuations in the OFDM signal. For example, M may be equal to 10(N+G).

[0089] Furthermore, the coarse time synchronization circuit **66** corrects short-term fluctuations in the signals by utilizing the training symbols, pilot symbols, and the instantaneous energy value p_n generated by the AGC circuit **80**. After the coarse time synchronization circuit **66** determines an approximate starting time, a more precise time synchronization is achieved by utilizing the fine time synchronization circuit **72**, which preferably follows in sequence after a frequency offset estimation operation, as will be described below.

[0090] In addition to the feedback signal to the pre-amplifier **57**, the coarse time synchronization circuit **66** outputs the coarsely synchronized signals to the first frequency offset estimation circuit **68 (FIG. 8)** for carrying out the first step of frequency offset estimation and correction. In accordance with the present invention, frequency synchronization is preferably carried out in two steps. The first frequency offset estimation circuit **68** estimates any frequency offset of ±½ sub-carrier spacings where $I=N/N_I$ and N_I is the length of the periodic sequence. In the simplest case, $N_I=N$ and the first frequency offset estimation circuit **68** can correct frequency offset of one sub-carrier spacing. This frequency offset is derived from the phase output from the auto-correlation circuit **75**, when the auto-correlation reaches its peak or crosses a certain predetermined threshold.

[0091] An example embodiment of the first frequency offset estimation circuit **68** is illustrated in **FIG. 10**. The phase output from the auto-correlation circuit **75** is input into an offset estimation circuit **86**. The offset estimation circuit **86** estimates the frequency offset using a formula that may be expressed by:

$$\gamma = \frac{N}{2\pi N_I} \theta$$

[0092] If the range of the first frequency offset estimation circuit **68** is not large enough, then the frequency offset

estimation has to be performed in two stages. The first frequency offset estimation circuit **68** estimates the fractional portion of the frequency offset.

[0093] The frequency offset of the integer multiples of the subcarrier spacings is performed by the second frequency offset estimation circuit **70** by performing a cyclic cross-correlation in the frequency domain. The cyclic cross-correlation is made possible by the fact that the training sequence structure is designed such that the same sequence is transmitted from all the transmitting antennas **18** in the first training symbol period. The second frequency offset estimation circuit **70** receives feedback from the output of a Discrete Fourier Transform (DFT) stage **64** (**FIG. 7**), which converts the signal into the frequency domain, and is compared (cross-correlated) with the training symbol that was transmitted. If there is any residual frequency offset of an integer multiple of sub-carrier spacings, then the peak of the cross-correlation function will have shifted by an appropriate number of sub-carriers. Otherwise the peak will be at zero frequency. This residual frequency offset estimate is then applied to the frequency offset correction circuit **74** to correct the residual offset. The second frequency offset estimation circuit **70** can also be used to provide a feedback signal to correct and adjust the frequency of the local oscillator **59**.

[0094] **FIG. 11** illustrates an example of an embodiment of the way in which the second frequency offset estimation circuit **70** shown in **FIG. 8** can be configured. An output from the DFT **64** is input as a frequency domain received symbol R_I to a buffer **88**, which stores in memory N samples. Outputs from the buffer **88** are input into N mixers **90**. Sequences S_I from the first frequency offset estimation circuit **68** are input into another buffer **92**, which stores the sequence S_I having a length of N samples. Sequence S_I is constructed by first repeating the sequence s_1 in the time domain I times and then taking an N-point FFT of the repeated sequence. Outputs from the buffer **92** are input into complex conjugation circuits (CCCs) **94** for performing complex conjugation operations. The outputs of the CCCs **94** are input into second inputs into the mixers **90**, which mixes the two sets of inputs. The outputs from the mixers **90** are sent to a summing circuit **96**, which provide a function having the equation:

$$\chi_k = \sum_{n=0}^{N-1} \left(S^*_{I,(k+n)_N} R_{I,n}\right) \quad k = 0, 1, \ldots, N-1,$$

k=0,1, . . . , N-1,

[0095] where (k+n)N represents the modulo-N or the remainder operation such that if k+n=N, then $(k+n)_N$=0 and if k+n—N+1, then $(k+n)_N$=1. Hence, the buffer **92** circularly shifts the sequence N times and calculates the values of χ from k=0 to N-1. The index k at which X achieves its maximum gives the frequency offset estimate of the integral number of sub-carrier spacings.

[0096] The output from the summing circuit **96** is sent to the frequency offset correction circuit **74** (**FIG. 8**), the fine time synchronization circuit **72**, and the local oscillator **59**. In response to this output, the frequency offset correction circuit **74** further corrects the frequency difference to synchronize the frequency with respect to the integer multiples. The local oscillator **59** responds by adjusting the sub-carrier frequency to minimize the frequency offset.

[0097] The frequency offset correction circuit **74** receives the estimates of the frequency offset from the first frequency offset estimation circuit **68** and the second frequency offset estimation circuit **70**. In response to the estimates in the frequency offset, the frequency offset correction circuit **74** can correct the frequency offset in discrete time or partly in discrete time and partly by sending the correction factor to the local oscillator **59**.

[0098] Fine time synchronization can then be achieved by using the fine time synchronization circuit **72** to find the start of the useful portion of the OFDM block to within a few samples. Fine time synchronization can be performed by cross-correlating the transmitted training symbols with the received frequency offset corrected signals from the frequency offset correction circuit **74** and by recognizing a predetermined pattern. If different sequences are transmitted from different antennas, then Q such correlation circuits are needed and the magnitudes of their outputs are summed together. The peak of the summed magnitudes will indicate the fine time synchronization instant. In the example of the transmission matrix structure provided in equations (1) and (2), the same sequence is transmitted from all the transmitting antennas 18 in the first OFDM symbol period. Hence, for this case, only one such correlation circuit is required and the sequence that is stored in the buffer is the time domain counterpart of the sequence S_1.

[0099] If deemed desirable, sequences with special properties can be transmitted from each antenna to further enhance the performance of the fine time synchronization circuit **72**. These properties could include the orthogonal nature of the transmitted sequences or any other variation on the sequences to be transmitted from different antennas.

[0100] **FIG. 12** illustrates an example embodiment of the fine time synchronization circuit **72**. In **FIG. 12**, a buffer **100** comprises a memory device for storing N_I samples. The buffer 100 receives the received samples r_n from the second frequency offset estimation circuit **70**. A second buffer **104** stores the time domain sequence s_1 having the length N_I, wherein S_I is the replica of the original transmitted sequence or a semblance of the transmitted sequence s_1. Each output from the buffer **100** is input into a first input of a number of N_I mixers **102**. The outputs from the buffer **104** are input into a number of N_I CCCs **106**, which perform complex conjugate operations on the outputs from buffer **104**. Each output from the CCCs **106** is input into a second input of the N_I mixers **102**. The N_I number of combined signals from the mixers **102** are input into a summing circuit **108**, which sums the combined signals using equation:

$$\psi_n = \sum_{k=0}^{N_I-1} s^*_k \cdot r_{n+k}.$$

[0101] Fine time synchronization is achieved at a time instant n when the function Ψ attains a value greater than a predetermined threshold. The output from the summing circuit **108** represents the output of the synchronization circuit **61** and is sent to a cyclic prefix remover **62** (**FIG. 7**).

[0102] The performance of the fine time synchronization circuit **72** is dependent on the frequency offset estimation and correction. Presence of any frequency offset hampers the performance of the fine time synchronization circuit **72**. When no frequency offset exists, the timing information may be derived directly from the coarse time synchronization circuit **66**. Also, coarse time synchronization can be modified to provide better estimates by averaging the results of the coarse time synchronization circuits from different OFDM demodulators and over different times. The fine time synchronization circuit **72** provides an optimal time instant of the start of the received OFDM frame.

[0103] The communication system **6** may either employ L such synchronization circuits **61**, one for each OFDM demodulator **22** or it may employ certain parts of the synchronization circuit for all the OFDM demodulators **20** and certain parts that are common to the entire receiver **10**. For example, the OFDM modulators **22** may include individual time synchronization circuits **66** and **72** and frequency offset correction circuit **74**, but may share common frequency offset estimation circuits **68** and **70**. Alternatively, the receiver **10** may simply comprise a single synchronization circuit **61**.

[0104] Reference will now be made again to **FIG. 7**. Once the fine time synchronization circuit **72** achieves fine time synchronization, the frequency and time synchronized information is provided to the cyclic prefix remover **62**, which removes the cyclic prefixes inserted between each block of N symbols. The blocks of N samples are then serial-to-parallel converted using serial-to-parallel converter **63** and the parallel signals are input to the DFT stage **64**, which converts the time domain samples back to the frequency domain, thus completing synchronization and demodulation by the OFDM demodulators **22**.

[0105] Referring again to **FIG. 1**, the L number of demodulated signals from each of the L number of OFDM demodulators **22** are then input into the decoder **24**, which processes the demodulated signals. The decoder **24** may be configured in the manner shown in the example embodiment of **FIG. 13**. The decoder **24** comprises a space-time processor **110** and a parameter estimator **112**. Both the space-time processor **110** and parameter estimator **112** receive the signals from each of the L number of OFDM demodulators **22**.

[0106] An output from the parameter estimator **112** is input into a symbol demapper **116** and a set of outputs is input into the space-time processor **110**. The output of the space-time processor **110** is converted from parallel to serial by a parallel-to-serial converter **114** and then input to the symbol demapper **116**, which maps the symbols from the predetermined alphabet back to the data bits. The output from the symbol demapper **116** is input into a channel decoder **118**. The channel decoder **118** decodes the data symbols by checking the parity that was added to the symbols prior to transmission. Thus, the channel decoder **118** detects and corrects errors in the data symbols and outputs the data in its original form. There can be an exchange of information between the parameter estimator **112**, symbol demapper **116** and channel decoder **118** to create a feedback loop. If the channel decoder **118** detects too many errors in the training symbol such that correction of the errors is no longer possible, then an "excessive-error" indication is made to the parameter estimator **112**, which adjusts and corrects its estimates.

[0107] The communication system **6** of the present invention, including the synchronization circuit **61**, can be implemented in hardware, software, firmware, or a combination thereof. In the embodiments of the present invention, the communication system **6** can be implemented in software or firmware that is stored in a memory and that is executed by a suitable instruction execution system. If implemented in hardware, as in an alternative embodiment, the synchronization system can be implemented with any or a combination of the following technologies, which are all well known in the art: a discrete logic circuit having logic gates for implementing logic functions upon data signals, an application specific integrated circuit (ASIC) having appropriate combinational logic gates, a programmable gate array (PGA), a field programmable gate array (FPGA), digital signal processor (DSP), etc.

[0108] It should be emphasized that the above-described embodiments of the present invention are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the invention. Many variations and modifications may be made to the above-described embodiments of the invention without departing substantially from the principles of the invention. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

We claim:

1. An apparatus for synchronizing a Multi-Input, Multi-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) system, the apparatus comprising:

a number Q of OFDM modulators, each OFDM modulator producing a frame comprising at least one inserted symbol, a plurality of data symbols, and cyclic prefixes;

said number Q of transmitting antennas, each transmitting antenna connected to a respective OFDM modulator, for transmitting said frame over a channel;

a number L of receiving antennas for receiving the transmitted frames; and

said number L of OFDM demodulators, each OFDM demodulator corresponding to a respective receiving antenna, the L OFDM demodulators comprising a synchronization circuit, which processes the received frame in order to synchronize the received frame in the time domain and frequency domain.

2. The apparatus of claim 1, wherein the cyclic prefixes protect the data symbols against Inter Symbol Interference (ISI).

3. The apparatus of claim 1, wherein the at least one inserted symbol has at least one pilot symbol inserted within the data symbols or at least one training symbol inserted at the beginning of the frame.

4. The apparatus of claim 1, wherein the synchronization circuit comprises a circuit for finding the optimum time instant of the start of the demodulated frame.

5. The apparatus of claim 4, wherein the synchronization circuit comprises a coarse time synchronization circuit and a fine time synchronization circuit.

6. The apparatus of claim 5, wherein the coarse time synchronization circuit comprises a circuit for performing auto-correlation on the received frame over a particular window.

7. The apparatus of claim 5, wherein the coarse time synchronization circuit comprises a circuit for performing an automatic gain control operation.

8. The apparatus of claim 1, wherein each of the Q OFDM modulators comprises a transmitting local oscillator, each of the L OFDM demodulators comprises a receiving local oscillator, and the synchronization circuit comprises a first frequency offset estimation circuit and a second frequency offset estimation circuit for estimating the frequency difference between the transmitting local oscillator and the receiving local oscillator.

9. The apparatus of claim 8, wherein the second frequency offset estimation circuit is used to correct the frequency of the receiving local oscillator.

10. The apparatus of claim 8, wherein said synchronization circuit further comprises a frequency offset correction circuit that utilizes the estimates from said second frequency offset estimation circuit and said first frequency offset estimation circuit to correct the frequency offset in discrete time.

11. The apparatus of claim 1, wherein each of the Q OFDM modulators share a common transmitting local oscillator, each of the L OFDM demodulators share a common receiving local oscillator, and the synchronization circuit comprises first and second frequency offset estimation circuits for estimating the frequency difference between the transmitting local oscillator and the receiving local oscillator.

12. The apparatus of claim 1, wherein Q is equal to L.

13. The apparatus of claim 12, wherein Q is equal to one.

14. The apparatus of claim 1, wherein Q equals two.

15. The apparatus of claim 1, wherein Q is not equal to L.

16. The apparatus of claim 1 further comprising an OFDM encoder, wherein the OFDM encoder comprises:

a channel encoder;

a symbol mapper connected to an output of the channel encoder;

a space-time processor connected to an output of the symbol mapper, the space-time processor separating data into a plurality of sub-channels; and

a pilot/training symbol inserter, which inserts pilot symbols and training symbols onto the sub-channels.

17. The apparatus of claim 1, wherein each of the Q OFDM modulators comprises:

a serial-to-parallel converter;

an inverse discrete Fourier transform (IDFT) stage connected to an output of the serial-to-parallel converter;

a cyclic prefix inserter connected to an output of the IDFT stage;

a parallel-to-serial converter connected to an output of the cyclic prefix inserter;

a digital-to-analog converter (DAC) connected to an output of the parallel-to-serial converter;

a local oscillator;

a mixer having a first input and a second input, the first input connected to an output of the DAC, the second input connected to an output of the local oscillator; and

an amplifier connected to an output of the mixer.

18. The apparatus of claim 1, wherein each of the L OFDM demodulators comprises:

a pre-amplifier;

a local oscillator;

a mixer having a first input and a second input, the first input connected to an output of the pre-amplifier, the second input connected to an output of the local oscillator;

an analog-to-digital converter (ADC) connected to an output of the mixer;

the synchronization circuit, having one input connected to an output of the ADC;

a cyclic prefix remover connected to an output of the synchronization circuit;

a serial-to-parallel converter connected to an output of the cyclic prefix remover; and

a discrete Fourier transform (DFT) stage connected to an output of the serial-to-parallel converter, an output of the DFT stage connected to another input to the synchronization circuit.

19. The apparatus of claim 1, wherein the L OFDM demodulators share a single synchronization circuit.

20. The apparatus of claim 1, wherein each OFDM demodulator uses one of L synchronization circuits.

21. The apparatus of claim 1, wherein the synchronization circuit comprises a first portion that includes individual circuits such that each individual circuit is used exclusively by a respective OFDM demodulator, and a second portion that includes circuits that are shared by all of the L OFDM demodulators.

22. The apparatus of claim 21, wherein the second portion comprises a first frequency offset estimator circuit and a second frequency offset estimator circuit, and the first portion comprises a coarse time synchronization circuit, a fine time synchronization circuit, and a frequency offset correction circuit.

23. The apparatus of claim 21, wherein the second portion comprises a coarse time synchronization circuit, a first frequency offset estimator circuit, and a second frequency offset estimator circuit, and the first portion comprises a fine time synchronization circuit and a frequency offset correction circuit.

24. The apparatus of claim 21, wherein the first portion comprises coarse time synchronization circuits wherein the results of the different coarse time synchronization circuits are shared by the different OFDM demodulators.

25. The apparatus of claim 1 further comprising an OFDM decoder, wherein the OFDM decoder comprises:

a space-time processor that receives an output from each of the L OFDM demodulators;

a parameter estimator that receives an output from each of the L OFDM demodulators and estimates parameters of the channel;

a parallel-to-serial converter connected to an output of the space-time processor;

a symbol demapper having a first input and second input, the first input connected to an output of the parameter estimator, the second input connected to an output of the parallel-to-serial converter; and

a channel decoder connected to an output of the symbol demapper.

26. A synchronization circuit, incorporated within a demodulator of a Multi-Input, Multi-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) system, wherein the synchronization circuit comprises:

a coarse time synchronization circuit;

a first frequency offset estimation circuit connected to a first output of the coarse time synchronization circuit;

a second frequency offset estimation circuit connected to a first output of the first frequency offset estimation circuit;

a fine time synchronization circuit having a first input connected to a first output of the second frequency offset estimation circuit; and

a frequency offset correction circuit having inputs connected to second outputs of the coarse time synchronization circuit, first frequency offset estimation circuit, and second frequency offset estimation circuit, and having an output connected to a second input to the fine time synchronization circuit.

27. The apparatus of claim 26, wherein the coarse time synchronization circuit is an auto-correlation circuit that comprises:

a delay circuit that receives a stream of data samples of the received frame;

a complex conjugation circuit connected to an output of the delay circuit;

a mixer having a first input and a second input, the first input receiving the stream of data samples, the second input connected to an output of the complex conjugation circuit; and

a summing circuit connected to an output of the mixer.

28. The apparatus of claim 26, wherein the first frequency offset estimation circuit comprises an offset correction circuit.

29. The apparatus of claim 26, wherein the second frequency offset estimation circuit is a cross-correlation circuit in the frequency domain that comprises:

a first buffer that receives and stores a portion of a stream of data samples from a Discrete Fourier Transform (DFT) stage, the first buffer having a plurality of outputs;

a second buffer that receives and stores a portion of a stream of data samples in the frequency domain from a transmitted sequence, the second buffer having a plurality of outputs;

a plurality of complex conjugation circuits connected to the plurality of outputs of the second buffer;

a plurality of mixers, each mixer having a first input and a second input, the first inputs connected to the outputs of the first buffer, the second inputs connected to outputs of the complex conjugation circuits; and

a summing circuit that sums the outputs of the mixers.

30. The apparatus of claim 26, wherein the fine time synchronization circuit is a cross-correlating pattern recognition circuit that comprises:

a first buffer that receives and stores a portion of a stream of data samples of the received frame, the first buffer having a plurality of outputs;

a second buffer that receives and stores a portion of a transmitted sequence in the time domain, the second buffer having a plurality of outputs;

a plurality of complex conjugation circuits connected to the plurality of outputs of the second buffer;

a plurality of mixers, each mixer having a first input and a second input, the first inputs connected to the outputs of the first buffer, the second inputs connected to outputs of the complex conjugation circuits; and

a summing circuit that sums the outputs of the mixers.

31. A method for synchronizing a Multi-Input Multi-Output (MIMO) Orthogonal Frequency Division Multiplexing (OFDM) system in the time and frequency domains, the method comprising the steps of:

producing a frame of data comprising a training symbol that includes a synchronization component that aids in synchronization, a plurality of data symbols, and a plurality of cyclic prefixes;

transmitting the frame over a channel;

receiving the transmitted frame;

demodulating the received frame;

synchronizing the received demodulated frame to the transmitted frame such that the data symbols are synchronized in the time domain and frequency domain.

32. The method of claim 31, wherein the synchronizing in the time domain comprises coarse time synchronizing and fine time synchronizing.

33. The method of claim 32, wherein the synchronizing in the time domain includes averaging estimates over a period of time.

34. The method of claim 31, wherein the synchronizing in the frequency domain comprises estimating a frequency offset.

35. The method of claim 34, wherein the step of estimating the frequency offset comprises estimating the frequency offset to within one half of the sub-carrier spacing.

36. The method of claim 35, wherein the step of estimating the frequency offset further comprises the steps of:

repeating received samples of the received frame a number of times;

taking an N-point Fast Fourier Transform (FFT); and

performing a cross-correlation procedure in the frequency domain.

37. The method of claim 34, wherein the step of estimating the frequency offset comprises averaging the estimates over a number of frames, thereby improving the estimates.

38. The method of claim 34, wherein the step of estimating the frequency offset comprises taking the estimates from

a number of different OFDM demodulators and averaging the estimates, thereby improving the estimates.

39. The method of claim 31, wherein the transmitting step includes transmitting the symbols from at least two antennas.

40. The method of claim 31, wherein the step of producing further comprises producing said training symbol with an orthogonal sequence, thereby enhancing the fine time synchronization performance.

41. The method of claim 31, wherein the step of producing further comprises adjusting the periodicity of the training symbol, thereby increasing the range of frequency offset estimation.

42. The method of claim 31, wherein the synchronization component aids in synchronization and in the estimation of channel parameters.

43. The method of claim 31, wherein the synchronization component comprises a preamble of a generalized length having a number of OFDM symbols less than a number of transmitting antennas.

44. The method of claim 31, wherein the synchronization component comprises a preamble of a generalized length having a number of OFDM symbols equal to a number of transmitting antennas.

45. The method of claim 31, wherein the synchronization component comprises a preamble of a generalized length having a number of OFDM symbols greater than a number of transmitting antennas.

46. The method of claim 31, wherein the synchronization component comprises a preamble whose signal transmission matrix resembles an existing space-time block code.

47. The method of claim 31, wherein the synchronization component includes chirp-like sequences.

48. The method of claim 47, wherein the chirp-like sequences include at least one of Frank-Zadoff sequences, Chu sequences, Milewski sequences, Suehiro polyphase sequences, and Ng et al. sequences.

49. The method of claim 31, wherein the step of producing a frame comprises producing the cyclic prefixes in a preamble and in the data symbols such that the cyclic prefixes in the preamble are longer than the cyclic prefixes in the data symbols, thereby countering an extended channel impulse response and improving synchronization.

50. The method of claim 31, further comprising the step of altering the training symbol to enhance the synchronization performance.

51. The method in claim 31, wherein the coarse time synchronizing includes averaging the coarse time synchronized results over time.

52. The method of claim 31, further comprising the steps of:

generating an N-point representation of the transmitted sequence in the frequency domain;

repeating the time domain sequence a number of times; and

taking an N-point Fast Fourier Transform.

53. The method of claim 31, wherein the step of producing comprises producing a preamble whose signal transmission matrix resembles an existing space-time block code.

* * * * *

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(54) **CHANNEL ESTIMATION FOR WIRELESS SYSTEMS WITH MULTIPLE TRANSMIT ANTENNAS**

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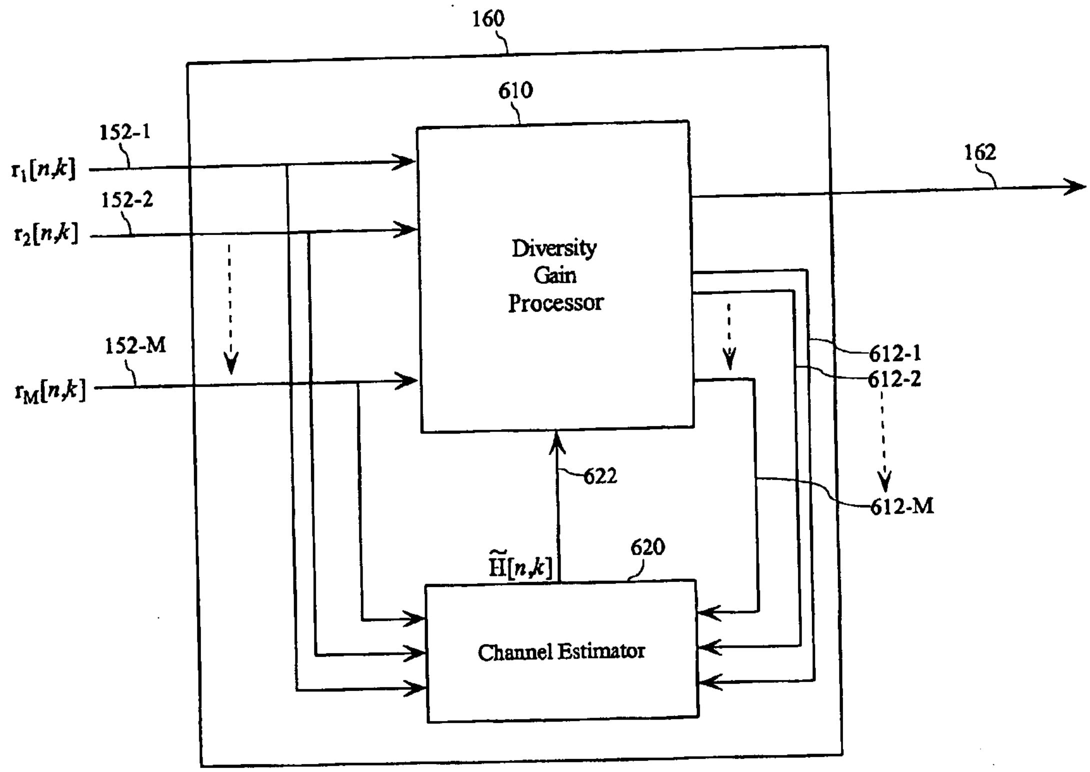
(57) **ABSTRACT**

In various embodiments, techniques are provided to determine channel characteristics of various communication systems such as OFDM systems or systems using a plurality of transmit antennas by using various sets of training symbols.



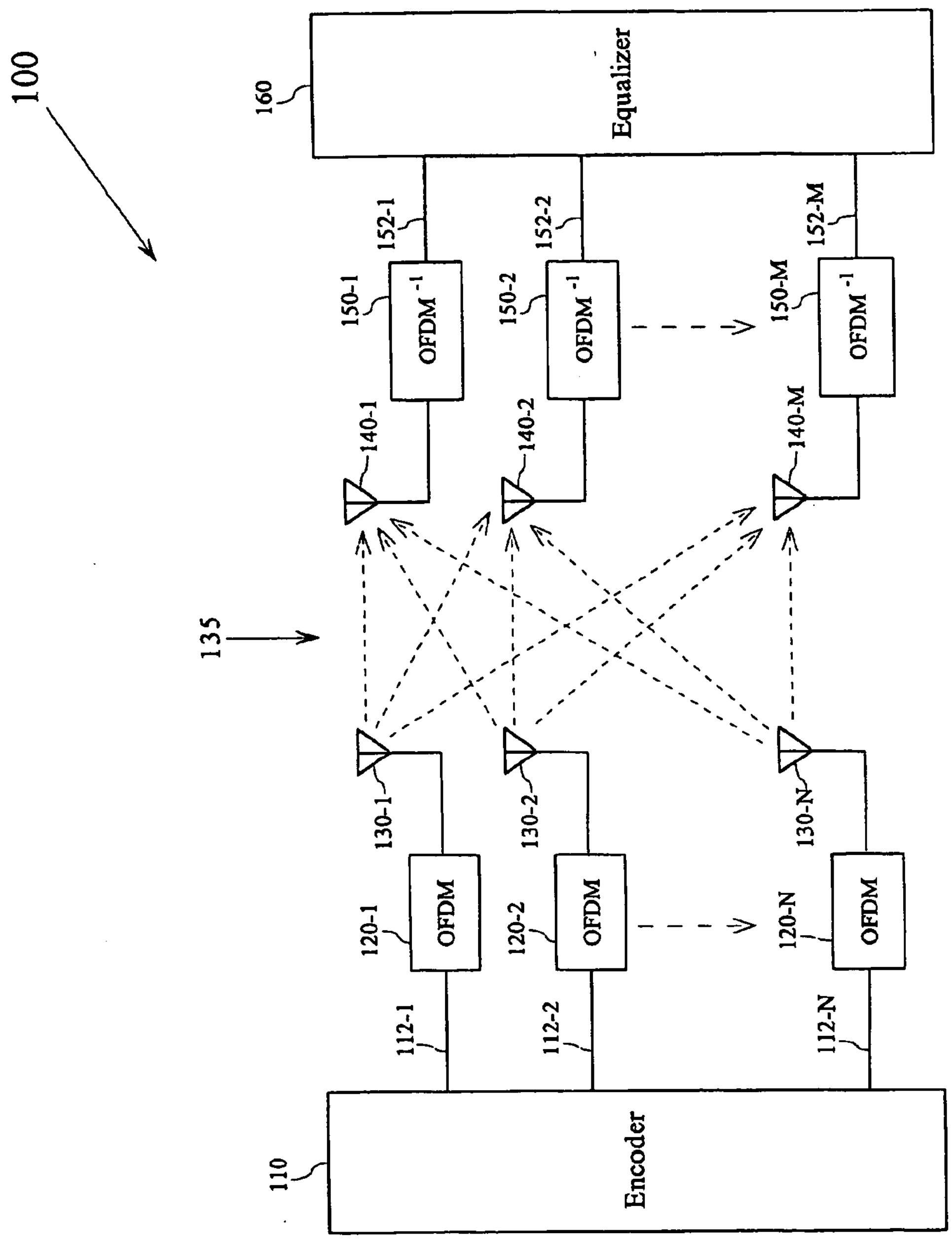

100
160
Equalizer
152-1
152-2
152-M
150-1
150-2
150-M
OFDM $^{-1}$
OFDM $^{-1}$
OFDM $^{-1}$
140-1
140-2
140-M
135
130-1
130-2
130-N
120-1
120-2
120-N
OFDM
OFDM
OFDM
112-1
112-2
112-N
110
Encoder

Fig. 1

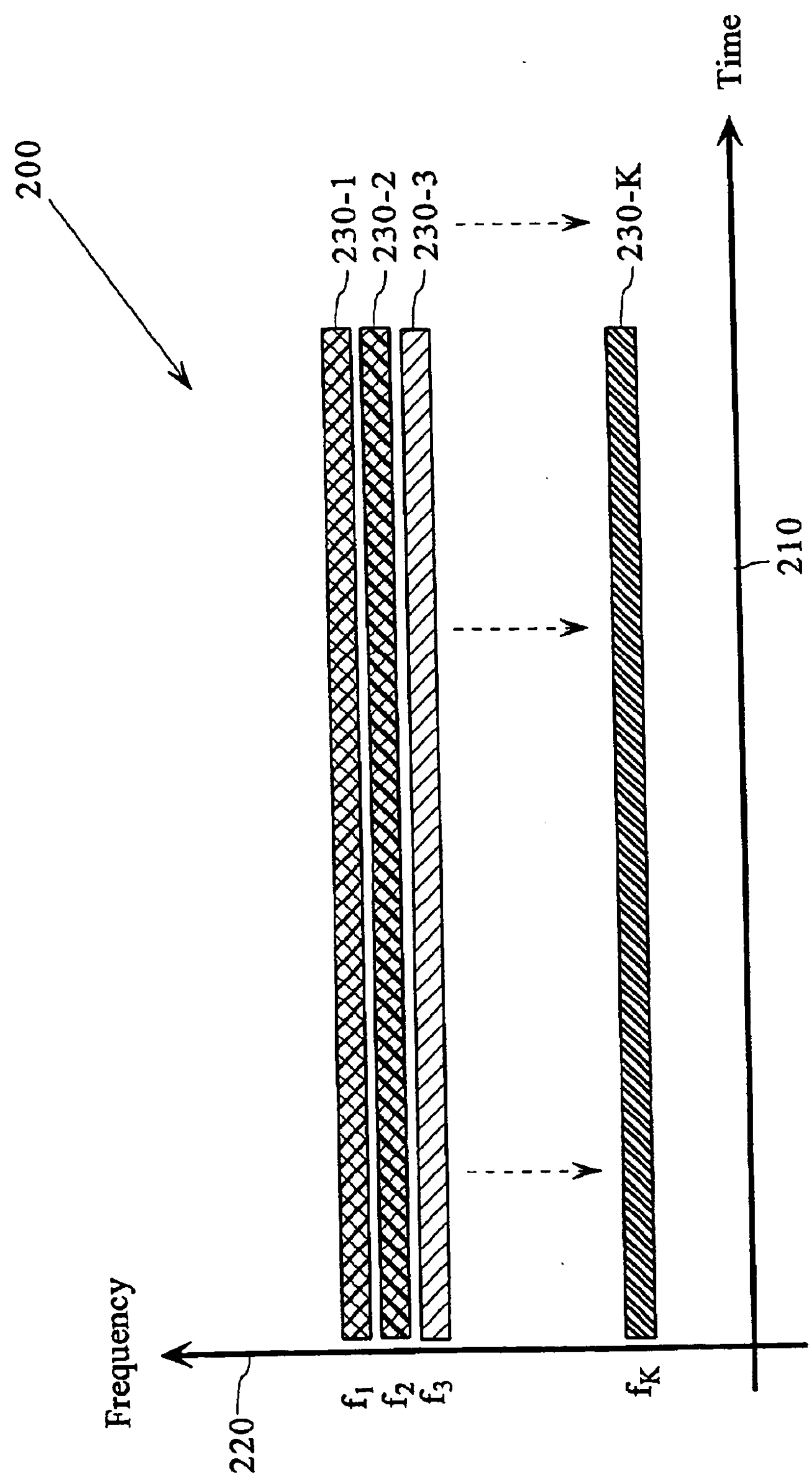


Fig. 2

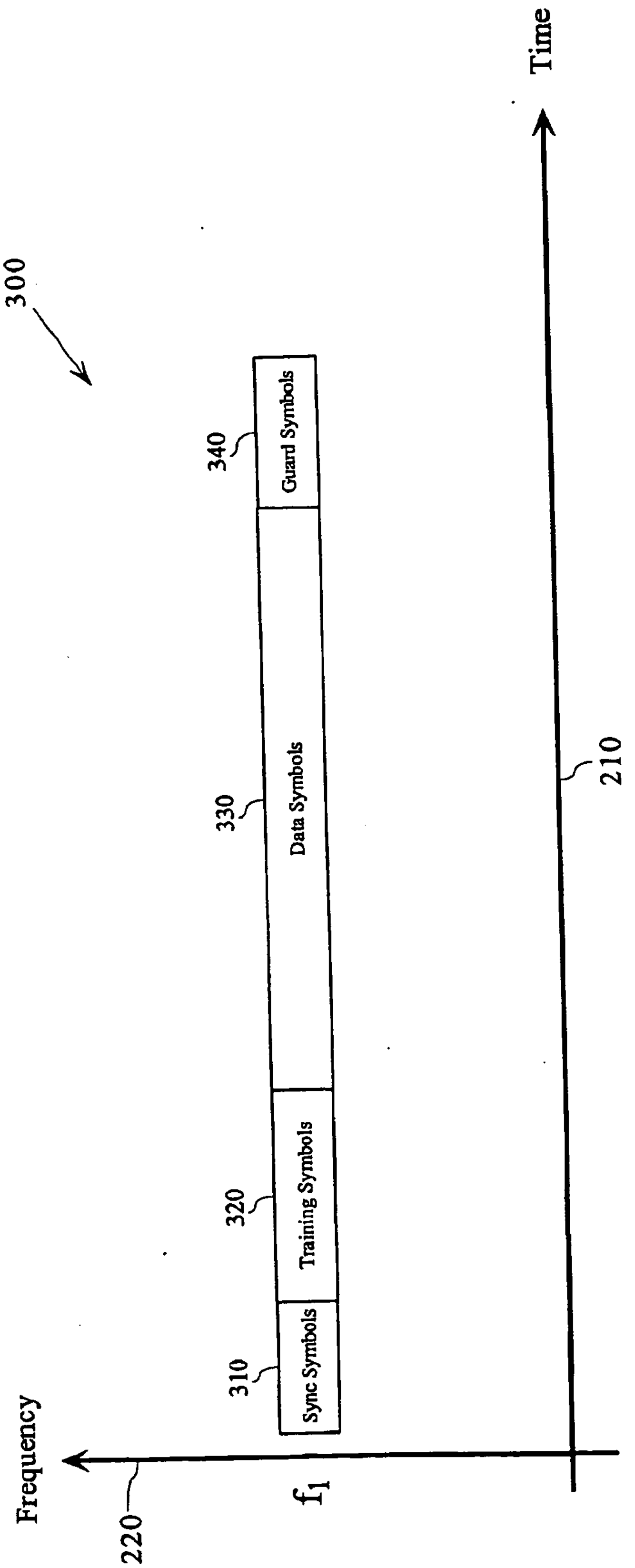

Time
300
340
Guard Symbols
330
Data Symbols
320
Training Symbols
310
Sync Symbols
210
Frequency
220
f_1

Fig. 3

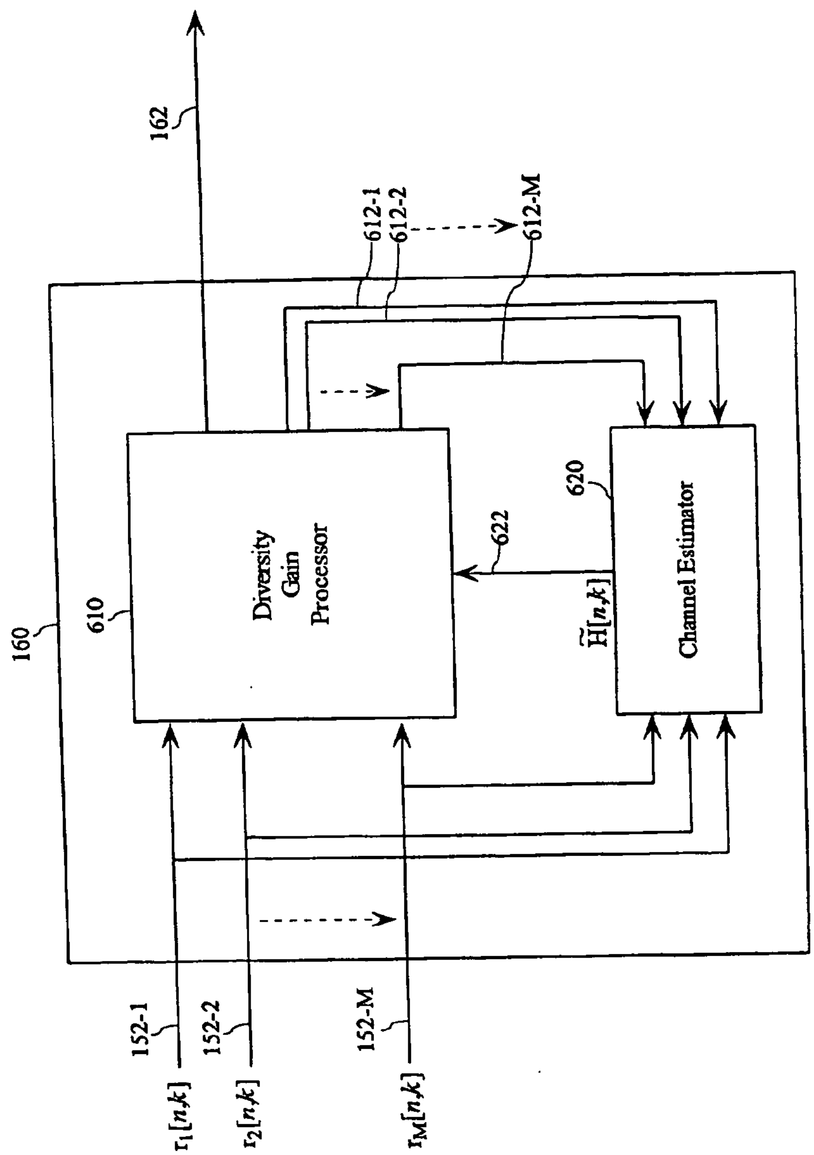

162
612-1
612-2
612-M
160
610
Diversity Gain Processor
622
620
Channel Estimator
$\tilde{H}[n,k]$
152-1
152-2
152-M
$r_1[n,k]$
$r_2[n,k]$
$r_M[n,k]$

Fig. 4

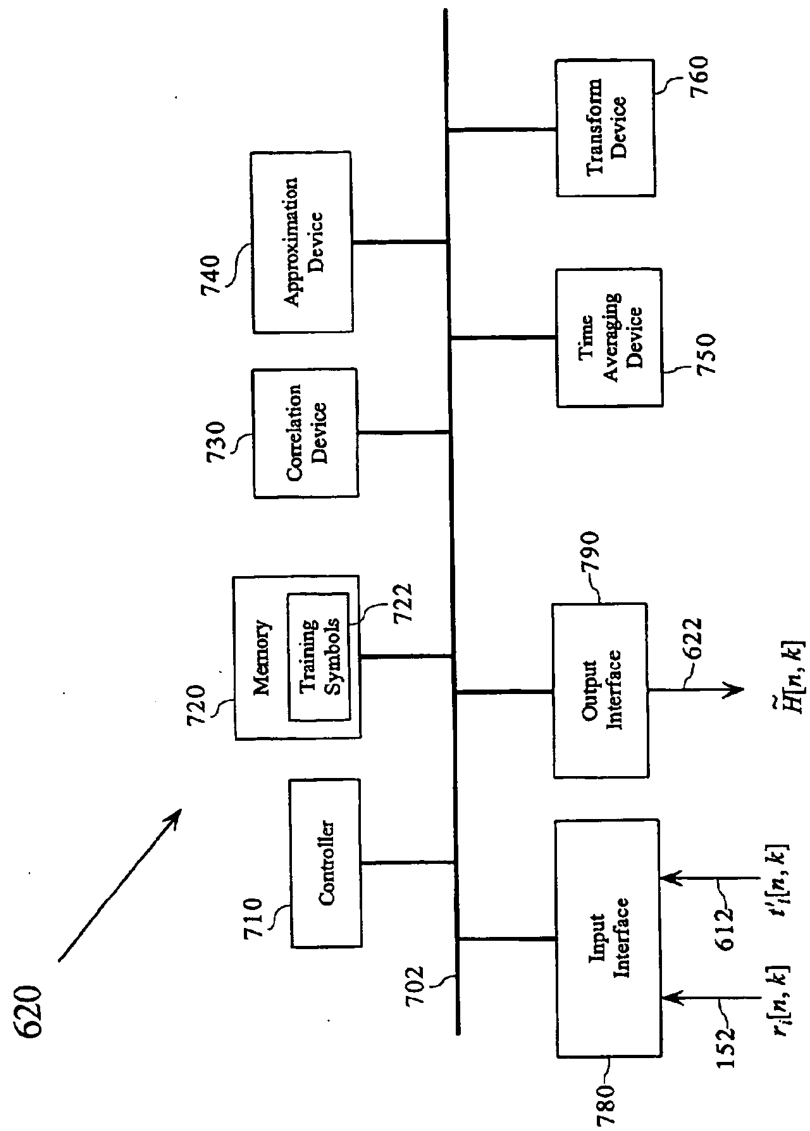

620
Controller
710
Memory
Training Symbols
720
722
Correlation Device
730
Approximation Device
740
702
Transform Device
760
Time Averaging Device
750
Output Interface
790
622
$\tilde{H}[n, k]$
Input Interface
780
612
152
$t'_i[n, k]$
$r_i[n, k]$

FIG. 5

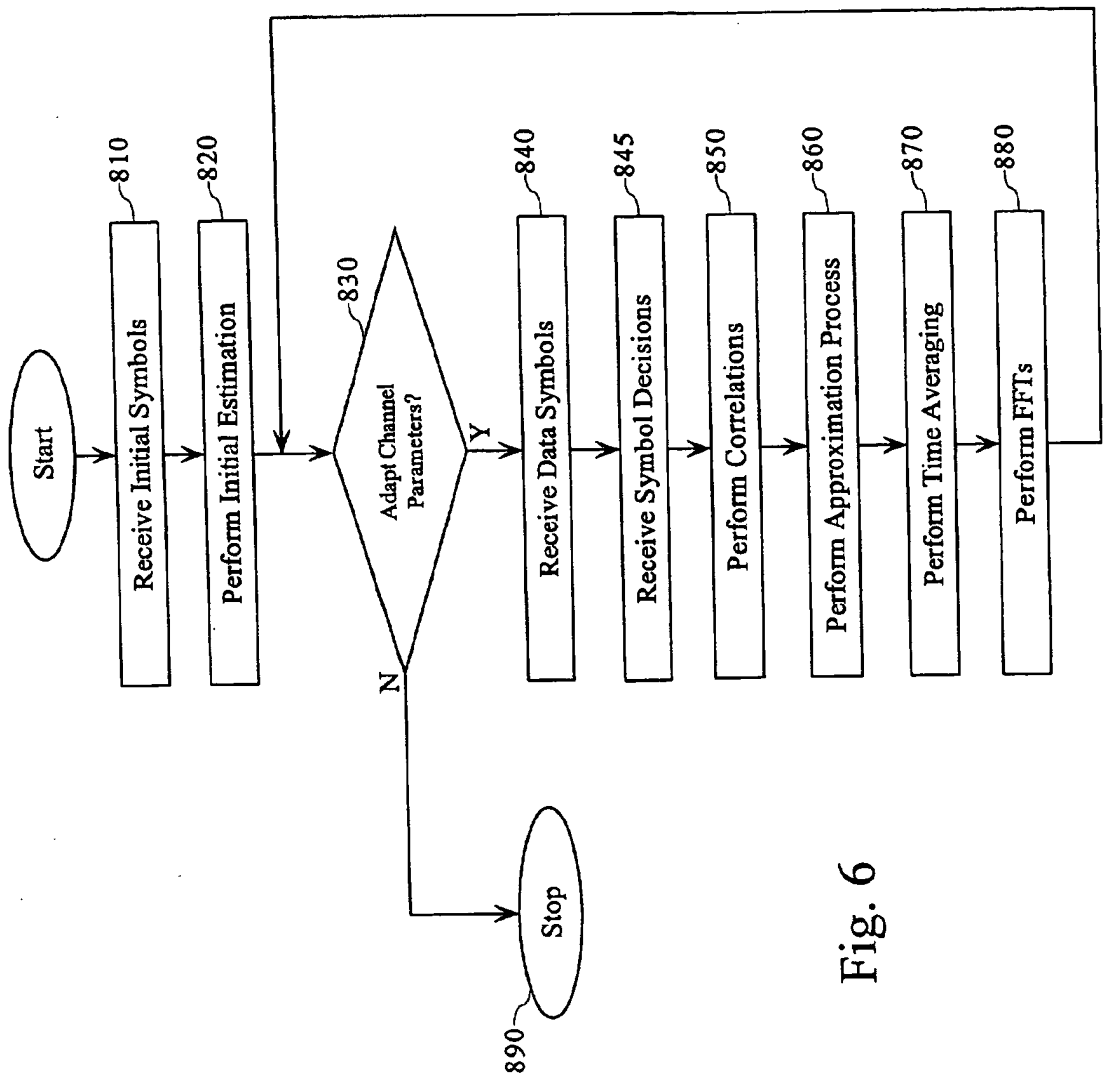

Start
Receive Initial Symbols
810
Perform Initial Estimation
820
Adapt Channel Parameters?
830
Y
N
Receive Data Symbols
840
Receive Symbol Decisions
845
Perform Correlations
850
Perform Approximation Process
860
Perform Time Averaging
870
Perform FFTs
880
Stop
890

Fig. 6

CHANNEL ESTIMATION FOR WIRELESS SYSTEMS WITH MULTIPLE TRANSMIT ANTENNAS

BACKGROUND OF THE INVENTION

[0001] 1. Field of Invention

[0002] This invention relates to channel estimation in wireless systems.

[0003] 2. Description of Related Art

[0004] As wireless communications systems are deployed around the world, the importance of providing clear and cost-effective communication services increases. Unfortunately, providing clear communications can require mitigating various obstacles such as inter-symbol-interference (ISI). To reduce ISI, a technique known as orthogonal frequency division multiplexing (OFDM) can be used. Orthogonal frequency division multiplexing is a communication paradigm where a single communication channel is divided into many narrow sub-bands, which then can be transmitted in parallel. By transmitting symbols in this fashion, the duration of each symbol can be dramatically increased, which can greatly reduce or completely eliminate ISI problems.

[0005] Unfortunately, individual sub-bands within an OFDM transmission are subject to Rayleigh fading, especially when used in mobile communication systems. While the effects of Rayleigh fading can be mitigated by using multiple transmitter and/or receiver antennas, estimating the channel characteristics for all transmitter-receiver antenna pairs can be difficult and computationally intensive. Accordingly, there is a need for apparatus and techniques that provide for better channel estimation.

SUMMARY OF THE INVENTION

[0006] In various embodiments, techniques are provided to determine channel characteristics of various communication systems such as OFDM systems or systems using a plurality of transmit antennas.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The invention is described in detail with regard to the following figures, wherein like numerals reference like elements, and wherein:

[0008] **FIG. 1** is a block diagram of an exemplary communication system;

[0009] **FIG. 2** depicts an OFDM signal having multiple sub-bands;

[0010] **FIG. 3** depicts an exemplary communication signal of an OFDM sub-band;

[0011] **FIG. 4** is a block diagram of an equalizer with an exemplary channel estimator;

[0012] **FIG. 5** is a block diagram of the exemplary channel estimator of **FIG. 4**; and

[0013] **FIG. 6** is a flowchart outlining an exemplary technique for estimating communication channels.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0014] For wireless systems, channel estimation can be difficult and computationally intensive. For wireless communication systems such as orthogonal frequency division multiplexing (OFDM) systems that use multiple sub-bands, computational costs can increase since each sub-band must be estimated. Furthermore, because practical OFDM systems can require multiple transmit and/or receive antennas, the computational costs can rise to enormous levels as each sub-band for each transmit/receive antenna pair must be estimated.

[0015] Regardless of such computational costs, the difficulty of channel estimation is further complicated in the context of mobile systems because the characteristics of mobile channels can continually change over time. Thus, even if every OFDM sub-band for every transmit/receive antenna pair is accurately modeled at the start, middle or end of a communication, such channel estimates can be totally inadequate for other portions of the communication.

[0016] Generally, a mobile channel can be estimated by embedding a set of predetermined symbols known as training symbols at a transmitter and processing the training symbols at a receiver to produce a set of initial channel estimates. For continually changing channels such as mobile channels, the initial channel estimates can then be iteratively updated, or adapted, over time by appropriately processing subsequent data symbols. For example, a set of training symbols in a received signal can be used to estimate a set of initial channel estimates $\hat{H}[n]$ that, in turn, can be used to equalize the received signal. The set of initial channel estimates $\hat{H}[n]$ can then be updated using the equalized received signal to adapt the channel estimates to track the changing channel environment, i.e., $\hat{H}[n+1=\Phi[\hat{H}[n]]$ where Φ is some predetermined function and n+1 relates to a frame of data processed after frame n.

[0017] Unfortunately, determining the various sets of channel estimates for communication systems having multiple antennas can require the formation and use of a cross-correlation matrix Q that must be subsequently inverted. As the size of the cross-correlation matrix Q grows, the computational requirements to invert Q can grow geometrically. While judiciously choosing training symbols can eliminate the need to invert the cross-correlation matrix Q, data symbols, unlike training symbols, cannot be so chosen.

[0018] However, by making various assumptions about the data symbols, sets of updated channel estimates can be estimated without inverting the cross-correlation matrix Q, and computational costs can be vastly reduced with only a minor degradation in the accuracy of the channel estimates.

[0019] **FIG. 1** is a block diagram of an exemplary transmission system **100**. The transmission system **100** includes an encoder **110** having a number of associated OFDM transmitters **120-1**, **120-2**, . . . **120-N** and respective transmit antennas **130-1**, **130-2**, . . . **130-N**, and an equalizer **160** having a number of associated OFDM receivers **150-1**, **150-2**, . . . **150-M** with respective receive antennas **140-1**, **140-2**, . . . **140-M**.

[0020] In operation, the encoder **110** can form blocks of symbols that can be provided to the various OFDM transmitters **120-1**, **120-2**, . . . **120-N**. The various OFDM

transmitters **120-1, 120-2**, . . . **120-N**, in turn, can modulate the blocks of symbols into electromagnetic carriers such as radio-frequency waves that can then be transmitted using their respective transmitting antennas **130-1, 130-2**, . . . **130-N**. The various radio-frequency signals **135** can then be received by the receive antennas **140-1, 140-2**, . . . **140-M** and fed to their respective OFDM receivers **150-1, 150-2**, . . . **150-M**. The OFDM receivers **150-1, 150-2**, . . . **150-M** can then transform the received radio-frequency signals **135** into base-band signals, digitize the base-band signals and provide the digitized base-band signals to the equalizer **160**. The equalizer **160**, in turn, can extract the symbols from the digitized base-band signals and perform various operations on the symbols.

[0021] As shown in **FIG. 1**, the radio-frequency signals **135** transmitted by each transmit antenna **130-1, 130-2**, . . . **130-N** can be subsequently received by each of the receiving antennas **140-1, 140-2**, . . . **140-M**. While **FIG. 1** depicts the various communication channels as single direct paths between each transmit/receive antenna pair, it should be appreciated that each radio-frequency signal **135** can propagate from each transmit antenna **130-1, 130-2**, . . . **130-N** to each receive antenna **140-1, 140-2**, . . . **140-M** not only through a direct path, but can also propagate from each transmit antenna **130-1, 130-2**, . . . **130-N** to each receive antenna **140-1, 140-2**, . . . **140-M** through a variety of indirect paths (not shown).

[0022] The various radio-frequency signal paths for a particular transmit/receive antenna pair can produce a complex communication channel, which can be distinctly different from any other communication channel defined by another transmit/receive antenna pair. Generally, the channel characteristics of an individual mobile wireless channel i.e., the impulse response, can be described by Eq.(1):

$$h(t,\tau)=\sum_k \gamma_k(t)c(\tau-\tau_k), \tag{1}$$

[0023] where τ_k is the delay of the k-th path, $\gamma_k(t)$ is the corresponding complex amplitude for the k-th path, and c(t) is the shaping pulse for the k-th path whose frequency response is usually a square-root raised cosine Nyquist filter. When a communication channel is a mobile wireless channel, the motion of a vehicle can affect the complex amplitudes $\gamma_k(t)$'s, making each complex amplitude $\gamma_k(t)$ a wide-sense stationary (WSS), narrow-band complex Gaussian process, that can be independent for different signal paths.

[0024] From Eq. (1), the frequency response H(t,f) of a communication channel at time t can be described by Eq. (2):

$$H(t,f)\triangleq\int_{-\infty}^{+\infty}h(t,\tau)\exp(-j2\pi f\tau)\,d\tau \text{ or} \tag{2}$$

$$\triangleq C(f)\sum_k \gamma_k(t)\exp(-j2\pi f\tau_k) \tag{3}$$

[0025] where

$$C(f)\triangleq\int_{-\infty}^{+\infty}c(\tau)\exp(-j2\pi f\tau_k). \tag{4}$$

[0026] For OFDM systems with proper cyclic extension and timing, the channel frequency response can be expressed by Eq.(5):

$$H[n,k]\triangleq H(nT_f,k\Delta f)=\sum_{l=0}^{K_o-1}h[n,l]W_K^{kl} \tag{5}$$

[0027] where

$$h[n,l]\triangleq h(nT_f,kT_f/K),\ W_K^{kl}=\exp(-j2\pi kl/K),$$

[0028] K is the number of sub-bands (tones) in an OFDM block, k is an index designating a particular sub-band, l is a time domain index, T_{71} is the block length and Δ_f is the sub-band (tone) spacing.

[0029] Following Eq. (5), the frequency response at the k-th tone of an n-th block of OFDM symbols corresponding to an i-th transmit antenna can be expressed by Eq.(6):

$$H_i[n,k]=\sum_{l=0}^{K_o-1}h_i[n,l]W_K^{kl}. \tag{6}$$

[0030] Equation (6) demonstrates that $H_i[n, k]$ can be obtained by estimating or otherwise acquiring $h_i[n, k]$. Accordingly, the received signal r[n, k] at each receive antenna **140-1, 140-2**, . . . **140-M** can be expressed by Eq. (7):

$$r[n,k]=\sum_{i=1}^{M}H_i[n,k]t_i[n,k]+w[n,k], \tag{7}$$

[0031] where M is the number of transmit antennas, k denotes a particular OFDM sub-band and k=0, 1, . . . , K−1 for all n blocks. If the transmitted signals $t_i[n, k]$'s from each transmit antenna contain known signals such as training symbols, the temporal estimation of the various communication channels $h_i[n, l]$'s can be derived using Eq. (8):

$$\begin{pmatrix} Q_{11}[n] & Q_{12}[n] & \cdots & Q_{1P}[n] \\ Q_{21}[n] & Q_{22}[n] & & \vdots \\ \vdots & & \ddots & \\ Q_{PI}[n] & \cdots & & Q_{PP}[n] \end{pmatrix} \begin{pmatrix} \tilde{h}_1[n] \\ \tilde{h}_2[n] \\ \vdots \\ \tilde{h}_P[n] \end{pmatrix} = \begin{pmatrix} p_1[n] \\ p_2[n] \\ \vdots \\ p_P[n] \end{pmatrix}, \tag{8}$$

or

$$\begin{pmatrix} \tilde{h}_1[n] \\ \tilde{h}_2[n] \\ \vdots \\ \tilde{h}_P[n] \end{pmatrix} = \begin{pmatrix} Q_{11}[n] & Q_{12}[n] & \cdots & Q_{1P}[n] \\ Q_{21}[n] & Q_{22}[n] & & \vdots \\ \vdots & & \ddots & \\ Q_{PI}[n] & \cdots & & Q_{PP}[n] \end{pmatrix}^{-1} \begin{pmatrix} p_1[n] \\ p_2[n] \\ \vdots \\ p_P[n] \end{pmatrix}, \tag{9}$$

[0032] where

$$\tilde{h}_i[n] \triangleq (\tilde{h}_i[n, 0] \ldots, \tilde{h}_i[n, K_o - 1])^T, \tag{10}$$

$$Q_{ij}[n] \triangleq (q_{ij}[n, l-j])_{l,j=1}^{K_o}, \text{ and} \tag{11}$$

$$p_i[n] \triangleq (p_i[n, 0], \ldots, p_i[n, K_o - 1])^T, \tag{12}$$

[0033] where $\tilde{h}_i[n]$ is the estimated channel impulse response for the channel between an i-th transmit antenna and a particular receive antenna, $Q_{ij}[n]$ is the correlated energy between the set of training symbols $t_i[n, k]$ of an i-th transmit antenna and the set of training symbols $t_j[n, k]$ of a j-th transmit antenna and $p_i[n]$ is the cross-correlation vector between the set of training symbols $t_i[n, k]$ of an i-th transmit antenna and a received signal $r[n, k]$ at a particular receive antenna, and where:

$$q_{ij}[n, l] \triangleq \sum_{k=0}^{K-1} t_i[n, k] t_j^*[n, k] W_K^{-kl}, \text{ or alternatively,} \tag{13}$$

$$q_{ij}[n, l] \triangleq IFFT\{t_i[n, k] t_j^*[n, k]\}, \text{ and} \tag{14}$$

$$p_i[n, l] \triangleq \sum_{k=0}^{K-1} r[n, k] t_i^*[n, k] W_K^{-kl}, \text{ or alternatively,} \tag{15}$$

$$p_i[n, l] \triangleq IFFT\{r[n, k] t_i^*[n, k]\}. \tag{16}$$

[0034] From Eqs. (8) and (9), one can see that a matrix inversion is required to get the temporal estimation of each channel impulse response $h_i[n, k]$, i.e., $\tilde{H}=Q^{-1}P$.

[0035] **FIG. 2** depicts an exemplary OFDM signal **200** displayed along a time axis **210** and against a frequency axis **220**. As shown in **FIG. 2**, the OFDM signal **200** contains a number of individual sub-bands (tones) **230-1, 230-2,** . . . **230-K** with each respective sub-band centered on a respective one of closely spaced frequencies $f_1, f_2, \ldots f_K$. **FIG. 3** depicts an exemplary communication signal **300** capable of being embedded in the various sub-bands of **FIG. 2.** As shown in **FIG. 3**, the communication signal **300** contains a number of sync symbols **310**, a number of training symbols **320**, a number of data symbols **330** and a number of guard symbols **340**.

[0036] Data symbols, also known as payload symbols, can contain information to be transmitted. Guard symbols are symbols that can pad either or both of the beginning and end of a burst transmission and can be used for a variety of purposes including providing buffering, timing and synchronization. Sync symbols are predetermined symbols placed at various strategic positions within a block of data that can allow a receiver to synchronize or otherwise extract timing information from a transmitted signal.

[0037] Training symbols, like sync symbols, can be predetermined symbols placed at known positions. However, unlike sync symbols, training symbols are usually configured to enable an equalizer to estimate a given communication channel. It should be appreciated that, in various exemplary embodiments, the training symbols **320** can be any set of symbols suitable for training an equalizer. For example, the exemplary training symbols **320** can be formed taking into account various factors such as their suitability for clock recovery, frequency-shift estimation, their peak-to-average ratio of signal strength or any other known or later recognized factor useful for generating an advantageous or otherwise adequate training sequence.

[0038] As discussed above, training symbols can be selected such that inverting the cross-correlation matrix Q in Eq. (8) can be simplified. For example, various sets of training symbols can be selected such that a correlation between two different sets of training symbols is zero, thus reducing Eq. (9) above to the form of Eq. (17) below:

$$\begin{pmatrix} \tilde{h}_1[n] \\ \tilde{h}_2[n] \\ \vdots \\ \tilde{h}_i[n] \end{pmatrix} = \begin{pmatrix} Q_{11}[0] & 0 & \cdots & 0 \\ 0 & Q_{22}[0] & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & Q_{ij}[n] \end{pmatrix}^{-1} \begin{pmatrix} p_1[n] \\ p_2[n] \\ \vdots \\ p_i[n] \end{pmatrix} \tag{17}$$

[0039] Because all off-axis elements of the Q matrix are zero, determining the inverse matrix Q^{-1} can be greatly simplified. Furthermore, when the various transmitted signals are transmitted using a constant-modulus technique such as quadrature amplitude modulated (QAM), the absolute values of any transmitted symbols will be equal to one, i.e., ($|t_i[n, k]|=1$), the cross-correlation matrix Q can be reduced to Q=K×I, for all i =1, 2, . . . N, and Eq. (17) can be further reduced to the form of Eq. (18):

$$\begin{pmatrix} \tilde{h}_1[n] \\ \tilde{h}_2[n] \\ \vdots \\ \tilde{h}_i[n] \end{pmatrix} = \begin{pmatrix} K & 0 & \cdots & 0 \\ 0 & K & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & K \end{pmatrix}^{-1} \begin{pmatrix} p_1[n] \\ p_2[n] \\ \vdots \\ p_i[n] \end{pmatrix}, \text{ or} \quad (18)$$

$$\begin{pmatrix} \tilde{h}_1[n] \\ \tilde{h}_2[n] \\ \vdots \\ \tilde{h}_i[n] \end{pmatrix} = \frac{1}{K} \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{pmatrix} \begin{pmatrix} p_1[n] \\ p_2[n] \\ \vdots \\ p_i[n] \end{pmatrix} \quad (19)$$

[0040] Accordingly, the problem of determining channel characteristics can be reduced to solving Eq. (20):

$$h_i[n, l] = \frac{1}{K} p_i[n, l], \text{ or alternatively} \quad (20)$$

$$h_i[n, l] = \frac{1}{K} p_1[n, l-(i-1)\bar{K}_o] \quad (21)$$

[0041] for l=0, . . . , $\tilde{K}_0-1$, where $\tilde{K}_0$ is a number of samples and i=1, 2 . . . , N. Further details about the exemplary training symbols can be found in at least "Optimum training Sequences for Wireless Systems" by Ye LI (U.S. patent application Ser. No. ______, (Attorney Docket 1999-0759, 105493) concurrently filed and commonly assigned) incorporated herein by reference in its entirety including all references cited therein.

[0042] Returning to **FIG. 3**, it should be appreciated that, while the exemplary communication signal **300** is a burst signal with a particular form, it should be appreciated that the form of a burst signal can vary without departing from the spirit and scope of the present invention. For example, it should be appreciated that the training symbols **320** can be dispersed intermittently within the payload symbols **330**. It should further be appreciated that while the exemplary communication signal **300** is a burst signal, the communication signal **300** can take various other forms such as a continuous signal in which various training symbols can be periodically embedded.

[0043] **FIG. 4** is a block diagram of the exemplary equalizer **160** of **FIG. 1**. The exemplary equalizer **160** includes a diversity gain processor **610** and a channel estimator **620**.

[0044] In operation, the diversity gain processor **610** and channel estimator **620** can each receive various received signals $r_1[n, k]$, $r_2[n, k]$, . . . $r_M[n, k]$ such as blocks of symbols from OFDM transmissions via links **152-1, 152-2,** . . . **152-M**. The channel estimator **620** can then determine a set of initial channel estimates for each communication channel between a transmit/receive antenna pair.

[0045] As discussed above, each of the received signals $r_i[n, k]$ can contain multiple transmit signals $t_i[n, k]$'s according to Eq. (7) above transmitted by a plurality of transmit antennas, with each transmit signal $t_i[n, k]$ having an assortment of sync symbols, training symbols, data symbols and guard symbols, as well as any other symbol types. Also as discussed above, the training symbols embedded in the communication signals for each of the transmit signals $t_i[n, k]$ can be known symbol patterns and formed such that there is essentially no cross-correlated energy between each set of training symbols, i.e., $q_{ij}[n, l]=0$ for all $i \neq j$ such that a set of initial channel estimates can be determined using Eq. (18) above. Furthermore, when a QAM or other constant-modulus approach is used, a set of initial channel estimates can be determined using Eqs. (20) or (21) above. However, the particular form and respective computational efficiency of the training symbols can vary and can include any combination or sequence of symbols that can be used to determine the characteristic estimates of a communication channel without departing from the spirit and scope of the present invention.

[0046] While the exemplary estimator **620** can use a set of training symbols to determine a set of initial channel estimates, it should be appreciated that the estimator **620** can alternatively use any other symbol type, including data symbols, to determine sets of initial channel estimates. Still further, it should be appreciated that the exemplary estimator **160** can use any other known or later developed technique suitable to produce initial channel estimates without departing from the spirit and scope of the present invention.

[0047] After the communication channels have been initially characterized, the channel estimator **620** can export the sets of initial channel estimates to the diversity gain processor **610**, which can use the sets of channel estimates to provide spatial and temporal equalization on the received signals and produce streams of symbol decisions $t'_i[n, k]$ that can be exported to an external device (not shown) via link **162** and/or exported to the channel estimator **620** via links **612-1, 612-2,** . . . **612-M**.

[0048] As discussed above, because the channel characteristics can vary over time, especially in mobile communication system, it can be advantageous to periodically update, or adapt, a set of initial channel estimates. To determine updated channel estimates, one can start by reducing Eqs. (8) or (9) to the form of Eq. (22) below:

$$Q_{ii}[n]\tilde{h}_i[n] = p_i[n] - \sum_{g=1}^{i \neq g} Q_{gi}[n]\tilde{h}_g[n] \quad (22)$$

[0049] Then, when a communication system uses a constant modulus signal such as QAM, the correlation terms $Q_{11}[n]=Q_{22}[n]=\ldots=Q_{NN}[n]=K$ and Eq. (22) can be further reduced to Eq. (23) below:

$$\tilde{h}_i[n] = \frac{1}{K}\left(p_i[n] - \sum_{g=1}^{i \neq g} Q_{gi}[n]\tilde{h}_g[n]\right) \quad (23)$$

[0050] Equation (23) suggests that, if each $\tilde{h}_g[n]$ is known, then the $\tilde{h}_i[n]$ terms can be determined without a matrix inversion. Unfortunately, given that $\tilde{h}_i[n]$ is unknown, then $\tilde{h}_g[n]$ will not likely be known. However, by substituting a previously estimated channel estimate $\tilde{h}_g[n-1]$ for each $\tilde{h}_g[n]$ in Eq. **(23)**, Eq. **(23)** can be rewritten to the form of Eq. (24):

$$\tilde{h}_i[n] = \frac{1}{K}\left(p_i[n] - \sum_{g=1}^{i\neq g} Q_{gi}[n]\tilde{h}_g[n-1]\right) \tag{24}$$

[0051] While substituting $\tilde{h}_g[n-1]$ for each $\tilde{h}_g[n]$ can cause minor performance degradation, elimination of a matrix inversion using Eq. (24) can lead to major reductions in computational complexity.

[0052] Returning to **FIG. 4**, it should be appreciated that Eq. (24) suggests that the estimator **620** can produce updated channel estimates if the estimator **620** has access to previously determined channel estimates and known transmitted signals. While the estimator **620** can obviously retain past channel estimates, the estimator **620** must still find a source for known transmitted signals.

[0053] Fortunately, as discussed above, the diversity gain processor **610** can provide streams of symbol decisions $t'_i[n, k]$ to the estimator **620**. If properly equalized, the symbol decisions $t'_i[n, k]$ produced by the diversity gain processor **610** are likely the same as the transmitted symbols $t'_i[n, k]$. Accordingly, the estimator **620** can use the streams of symbol decisions $t'_i[n, k]$ as a substitute for $t_i[n, k]$ in Eqs. (13)-(16) above and determine sets of updated channel estimates using Eq. (24) above.

[0054] As the sets of updated channel estimates are produced, the estimator **620** can provide the sets of updated channel estimates to the diversity gain processor **610**. The diversity gain processor **610**, in turn, can use the sets of updated channel estimates to better equalize subsequently processed data symbols and produce streams of symbol decisions. The cycle of updating the channel estimates, adaptively equalizing the received signals and feeding symbol decisions back to the estimator **620** can then continue as required.

[0055] **FIG. 5** is a block diagram of the estimator **620** of **FIG. 4**. The estimator **620** includes a controller **710**, a memory **720** that contains various training symbols **722**, a correlation device **730**, an approximation device **740**, a time averaging device **750**, a transform device **760**, an input interface **780** and an output interface **790**. The various components **710-790** are coupled together by control/data bus **702**. Although the exemplary estimator **620** uses a bussed architecture, it should be appreciated that any other architecture may be used as is well-known to those of ordinary skill in the art.

[0056] In a first mode of operation, under control of the controller **710**, the input interface **780** can receive various known symbols via link **152**, and store the received symbols in the memory **720**. Next, the controller **710** can transfer the received symbols, as well as the training symbols **722** to the correlation device **730**. The correlation device **730** then can cross-correlate the received and training symbols according to Eqs. (15) or (16) above, and can further correlate the various training symbols according to Eqs. (13) or (14) above to produce first correlation products $p_i[n, l]$ and second correlation products $q_{ij}[n, l]$ respectively.

[0057] The first and second correlation products can then be transferred to the approximation device **740**, where the approximation device **740** can produce a set of initial channel estimates according to Eqs. (17)-(21) above. The initial set of channel estimates can then be exported to an external device (not shown) using the output interface **790** and link **622**.

[0058] While the first mode of operation can produce an initial set of channel estimates using Eqs. (13)-(21) above, it should be appreciated that the initial set of channel estimates can alternatively be produced by any other known or later developed technique that can determine or otherwise provide initial sets of channel estimates without departing from the spirit and scope of the present invention.

[0059] In a second mode of operation, under control of the controller **710**, the input interface **780** can accept other received symbols $r_i[n, k]$ via link **152** and also accept respective decision symbols $t'_i[n, k]$ via link **612**, which can then be stored in memory **720**.

[0060] Next, the controller **710** can transfer the various received symbols and decision symbols to the correlation device **730**, where the correlation device **730** can again form various first and second correlation products according to Eqs. (13)-(16) above. The correlation device **730** can then export the first and second correlation products to the approximation device **740**.

[0061] The approximation device **740** can receive the first and second correlation products and perform a first pre-estimation process according to Eqs. (25) or (26) below to produce sets of pre-estimates $\bar{h}_i[n]$:

$$\bar{h}_i[n] = \frac{1}{K} p_i[n] \text{ for } n = 1 \tag{25}$$

$$\bar{h}_i[n] = \frac{1}{K}\left(p_i[n] - \sum_{g=1}^{i\neq g} Q_{gi}[n]\tilde{h}_g[n-1]\right) \text{for } n = 2, 3, 4 \ldots \tag{26}$$

[0062] As shown by Eq. (25), if a first block n is being processed, i.e., the estimator **620** is estimating a set of initial channel estimates without training symbols, the set of initial channel pre-estimates are proportional to the first correlation products $p_i[n]=\{\Sigma p_i[n, l]$, where $l=1, 2, \ldots M\}$. However, for subsequent blocks of data, or when an initial set of channel estimates has been otherwise provided, the approximation device **740** can produce various sets of pre-estimates according to Eq. (26). Once the approximation device **740** has determined the appropriate sets of pre-estimates, the approximation device **740** can export the sets of pre-estimates to the time averaging device **750**.

[0063] The time averaging device **750** can receive the sets of pre-estimates and perform a time averaging operation on pre-estimates to produce sets of time-averaged estimates according to Eq. (27) below:

$$\hat{h}_i[n, l] = \Phi(\bar{h}_i[n, l]) = \sum_{m=0} f_k \bar{h}_i[n-m, l], \tag{27}$$

[0064] where f_k is a time-averaging coefficient. Details about time-averaging coefficients can be found in at least

"Channel Estimation for OFDM Systems with Transmitter Diversity" by Li, Y. and Ariyavisitakul, S. (U.S. patent application Ser. No. 09/215,074) herein incorporated by reference in its entirety.

[0065] While the exemplary time averaging device **750** uses the approach outlined by Eq. (27), it should be appreciated that, in various embodiments, the time averaging device **750** can determine or otherwise approximate time-averaged estimates according to any known or later developed technique without departing from the spirit and scope of the present invention.

[0066] After the time averaging device **750** produces the sets of time-averaged estimates, the sets of time-averaged estimates can be provided to the transform device **760** where the transform device **760** can determine sets of updated channel estimates according to Eq. (28) below:

$$\hat{H}_i[n,k]=FFT\{\hat{h}[n,l]\} \quad (28)$$

[0067] While the exemplary transform device **760** produces sets of updated channel estimates using a fast Fourier transform (FFT), it should be appreciated that any other known or later developed technique or approach that can determine or otherwise approximate channel estimates using time-averaged estimates can be used, such as a direct Fourier transform, a convolution process and the like, without departing from the spirit and scope of the present invention.

[0068] After the transform device has produced the various updated channel estimates, the transform device **760** can export the sets of updated channel estimates via the output interface **790** and link **622** to an external device. The estimator **620** can then repeat the process of importing and processing various received symbols and decision symbols to produce sets of updated channel estimates such that an equalizer using the updated estimates can adaptively track the changing characteristics of various communication channels and extract information from various received signals.

[0069] **FIG. 6** is a flowchart outlining an exemplary technique for producing various channel estimates according to the present invention. The operation starts in step **810** where a set of initial symbols is received. Next, in step **820**, a set of initial channel estimates is produced using the received symbols as well as various known training symbols according Eqs. (13)-(16) above. While the exemplary technique produces initial sets of channel estimates using known training symbols such as training symbols, as discussed above, the sets of initial channel estimates alternatively can be derived without training symbols using Eqs. (25)-(26) above. In still other embodiments, it should be appreciated that the sets of initial channel estimates can be derived or otherwise provided by any other known or later developed technique without departing from the spirit and scope of the present invention. The operation continues to step **830**.

[0070] In step **830**, a determination is made as to whether to update, or adapt, the sets of initial channel estimates. If the sets of initial channel estimates are to be adapted, control continues to step **840**; otherwise, control jumps to step **890** where the process stops.

[0071] In step **840**, further received symbols are accepted. Next, in step **845**, various respective symbol decisions are also accepted. Then, in step **850**, the received symbols and symbol decisions are correlated according to Eqs. (13)-(16) above to produce first and second correlation products. Control continues to step **860**.

[0072] In step **860**, an approximation technique is performed on the first and second correlation products to produce sets of pre-estimates according to Eqs. (25) or (26) above depending on whether initial sets of channel estimates are available. Next, in step **870**, a time averaging operation is performed on the sets of pre-estimates to produce sets of time-averaged estimates. Control continues to step **880**.

[0073] In step **880**, a transform is performed on the time-averaged estimates to produce sets of updated channel estimates. While the exemplary transform is a fast Fourier transform, as discussed above, any known or later developed transform useful to derive or otherwise approximate channel estimates using time-averaged estimates can be used without departing from the spirit and scope of the present invention. Control can then jump back to step **830** where another decision can be taken to update the various channel estimates. The various channel estimates can be continually updated according to steps **830**-**880** above until it is desirable or otherwise required to stop channel adaptation.

[0074] As shown in **FIG. 1-5**, the systems and methods of this invention are preferably implemented on a digital signal processor (DSP) or other integrated circuits. However, the systems and methods can also be implemented using any combination of one or more general purpose computers, special purpose computers, program microprocessors or microcontrollers and peripheral integrating circuit elements, hardware electronic or logic circuits such as application specific integrated circuits (ASICs), discrete element circuits, programmable logic devices such as PODs, POAs, FPGAs, PALs or the like. In general, any device on which exists a finite state machine capable of implementing the various elements of FIGS. **1-5** and the flowchart of **FIG. 6** can be used to implement the estimation functions.

[0075] While this invention has been described in conjunction with the specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, preferred embodiments of the invention as set forth herein are intended to be illustrative, not limiting. There are changes that may be made without departing from the spirit and scope of the present invention.

What is claimed is:

1. A method of characterizing one or more communication channels, comprising:

receiving a set of first symbols associated with a first communication channel;

receiving a set of second symbols associated with a second communication channel; and

characterizing at least a first communication channel based on at least the set of first symbols and the set of second symbols to produce a set of first channel characteristics;

wherein characterizing one or more communication channels is performed without a matrix inversion.

2. The method of claim 1, wherein the set of first symbols is received from a first transmit device and the set of second symbols is received from a second transmit device.

3. The method of claim 2, wherein the set of first symbols and the set of second symbols are received using a common receive device.

4. The method of claim 1, wherein at least the first communication channel is based on a constant-modulus technique.

5. The method of claim 3, wherein at least the first communication channel is further based on an orthogonal frequency division multiplexing technique.

6. The method of claim 4, wherein characterizing the first communication channel includes:

performing a first correlation to produce a set of first correlations; and

determining the set of first channel characteristics based on at least the set of first correlations.

7. The method of claim 6, wherein determining the set of first channel characteristics includes determining at least a set of first pre-estimates $\bar{h}_1[n]$.

8. The method of claim 7, wherein the set of first pre-estimates $\bar{h}_i[n]$ is determined based on the equation:

$$\bar{h}_i[n] = \frac{1}{K} p_i[n],$$

wherein $p_i[n]$ is the set of first correlations and K is a constant.

9. The method of claim 8, wherein characterizing the first communication channel further includes time-averaging at least one pre-estimate to produce a set of time-averaged estimates.

10. The method of claim 9, wherein characterizing the first communication channel further includes performing a transform on the set of time-averaged estimates to produce a set of channel characteristics.

11. The method of claim 1, wherein characterizing the first communication channel includes:

performing a first correlation to produce a set of first correlations;

performing a second correlation to produce a set of second correlations; and

determining a set of channel pre-estimates based on at least the first correlation product and the second correlation product.

12. The method of claim 11, wherein determining the set of first channel characteristics includes determining at least a set of first pre-estimates $\bar{h}_1[n]$.

13. The method of claim 12, wherein the set of first pre-estimates $\bar{h}_1[n]$is determined based on the equation:

$$\bar{h}_i[n] = \frac{1}{K}\left(p_i[n] - \sum_{g=1}^{i \neq g} Q_{gi}[n]\bar{h}_g[n-1]\right),$$

wherein $p_i[n]$ is related to the set of first correlations, $Q_{gi}[n]$ is related to the set of second correlations, and K is a constant and $\bar{h}_g[n-1]$ is related to a set of previously determined channel characteristics.

14. The method of claim 12, wherein characterizing the first communication channel further includes time-averaging at least one pre-estimate to produce a set of time-averaged estimates.

15. The method of claim 14, wherein characterizing the first communication channel further includes performing a transform on the a set of time-averaged estimates to produce a set of channel characteristics.

16. The method of claim 10, wherein characterizing two or more communication channels does not use a matrix inversion.

17. The method of claim 10, wherein the first set of training signals is transmitted using a first transmit device and the one of the one or more sets of second training signals is transmitted using a second transmitting device.

18. An apparatus for communicating, comprising:

a receive device that receives at least a set of first training symbols transmitted by a first transmit device and a set of second training symbols transmitted by a second transmit device; and

an estimator that estimates at least a first channel related to the first transmit device based on at least the set of first training symbols;

wherein a cross-correlation between the first set on training symbols and the sets of second training symbols is essentially zero.

19. The apparatus of claim 18, wherein the estimator further estimates the first channel based on at least the set of second training symbols.

20. The apparatus of claim 19, wherein the estimator estimates the first channel based without using a matrix inversion.

* * * * *